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ATOLL RESEARCH BULLETIN

8. *The Hydrology of Arno Atoll, Marshall Islands*
9. *The Coral Reefs of Arno Atoll, Marshall Islands*



Issued by

THE PACIFIC SCIENCE BOARD

National Academy of Sciences—National Research Council

Washington, D.C., U.S.A.

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It is a pleasure to commend the far-sighted policy of the Office of Naval Research, with its emphasis on basic research, as a result of which a grant has made possible the continuation of the Coral Atoll Program of the Pacific Science Board, including the launching of the Atoll Research Bulletin.

It is of interest to note, historically, that much of the fundamental information on atolls of the Pacific was gathered by the U. S. Navy's South Pacific Exploring Expedition, over one hundred years ago, under the command of Captain Charles Wilkes. The continuing nature of such scientific interest by the Navy is shown by the support for the Pacific Science Board's research programs, CIMA, SIM, and ICCP, during the past five years. The Coral Atoll Program is a part of SIM.

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THE HYDROLOGY OF ARNO ATOLL

MARSHALL ISLANDS

SCIENTIFIC INVESTIGATIONS IN MICRONESIA

Pacific Science Board

National Research Council

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Honolulu, Hawaii
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Profiles and ground-water graphs of two section across Ine Island.

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HYDROLOGY OF ARNO ATOLL

CLIMATE

The field investigation of the climate of Arno consisted of daily measurements of rainfall, maximum and minimum temperature, and humidity, and continuous recording of temperature and humidity. The principal weather station was at Ine Village on Ine Island on the south side of the atoll. Irregular rainfall measurements were also made on Bikarj Island and Arno Island. Due to shipping difficulties receipt of the meteorological equipment was delayed, and measurements were not started until July 2. All measurements were continued until the first week in September when the last of the party left Arno. Most of the records, therefore, cover a period of not quite two months. The Ine raingage was left in place, however, and Jokon, the scribe at Ine Village agreed to continue the daily measurements, sending the results monthly to Honolulu. As required, he will be assisted by William, the Ine school teacher.

The various measurements made so far constitute, by themselves, a hopelessly incomplete record of the Arno climate. The shorter periods of measurement will not indicate the changes even through a single seasonal cycle, and even a year's measurement of rainfall will give no indication of the limits of annual variation. However, they may be correlated with fragmentary but longer term records on the neighboring island of Majuro and with other records for Marshall Is., so that rough but useable definition of at least the hydrologic factors in the climate of Arno may be obtained.

The rainfall measurements recorded from July through November at Ine are tabulated in the appendix. The mean monthly rainfall has been 17 inches, equivalent to an annual rainfall of over 200 inches. As the record includes more summer months than winter months and as winter is reported to be the dry season, the actual annual rainfall will probably be somewhat less.

During the same period a mean monthly rainfall of 20 inches was recorded at Majuro. Most of the rainstorms are of small diameter, perhaps 10 miles across at the most. It is to be expected, therefore, that short period measurements at stations 10 miles or more away from each should show very poor correlation. Longer period totals, however, in which the effects of individual rainstorms are less important, should show greater correlation reflecting the movements of large air masses. The difference between the Ine rainfall and that of Arno, therefore, may well be a significant one. A long term estimate of the mean rainfall of Arno can probably be made when more complete records for Majuro and other Marshall Is. records become available and have been analyzed.

During a 24-day period the rainfall on Arno Island totalled 14 inches. The total for Ine for the same period was 16 inches and that at Majuro was 18 inches. This is interesting because the Arno station lies roughly between the Ine and Majuro stations yet its rainfall is not intermediate between that at Ine and Majuro but lower than either. The difference for the short period may, however, not be significant. Only four days rainfall in July were recorded at Bikarj. Afterwards the gage could not be visited until just before the party left Arno, when

it was found to be overflowing. As the total rainfall in the interim had been nearly 30 inches at Ine the overflow was to be expected, and the record contributes very little.

Daily rainfall during the period ranged from nil to over 4.14 inches. Most of this rain came in sudden intense rainstorms. No relation of rainstorm frequency to time of day was noted.

The temperature during the period of operation of the weather station ranged from 73° to 90° F. with a maximum daily range of 19° and a common daily range of 10° to 12°. The morning humidity readings ranged from 78% to 100%. The hydrothermograph records have not been analyzed, but casual inspection shows that the humidity usually dropped during the daytime, and that the humidity was generally between 80% and 95%.

TIDES

The tides of Arno were studied in some detail because of the importance of the elevation of the water table of the fresh ground-water bodies of the islands above mean sea level, and because of the importance of the tidal fluctuations in the fresh ground-water bodies of the islands. The shipping delay resulted in the loss of valuable recording time in this study also. One tide gage was established on the ocean side of Ine in the second week in July and a second was established on the lagoon side in the last week in July. The gages were kept in operation until just before the party left.

An analysis of the tide records by the Coast and Geodetic Survey indicates that the mean tide range in the ocean is 3.8 feet and the spring range is about 4.1 feet. The mean water level in the lagoon is

about the same as that in the ocean, but the mean tide range is 0.1 feet greater than that in the ocean. The explanation for this increase in tide range in the lagoon is not known.

A number of bench marks were established to facilitate leveling between tide gages and wells. Their description and elevations are listed in the appendix.

RAIN CATCHMENT

There is no runoff of the rainfall from the Island of Arno. At the most the water may run a few tens of feet on the packed surface of the main trails. Most of the rainfall seeps very quickly into the highly permeable soil. Artificial surface catchment of rainfall is, however, very important. It furnishes the entire supply of water for cooking and drinking in Ine and Arno villages and by far the major supply for those purposes generally. The best catchment structures are corrugated iron roofs. In Ine Village perhaps half of the houses have such roofs, totalling about 12,000 horizontal square feet of catchment surface. Of this surface not quite 6,000 square feet is actually used, the water being led by troughs to concrete cisterns or discarded oil drums. In Ine Village there are 22 cisterns totalling about 69,000 gallons storage volume. Of these, however, only 17, totalling 53,000 gallon capacity are actually in use. With the barrels the total water storage capacity in the village is about 54,000 gallons. This is the equivalent of nearly 150 inches of rain on the tributary catchment areas. However, the ratio of the catchment areas to the capacities of the cisterns and barrels they feed is extremely variable. On the one hand some cisterns are fed only by the

roofs that cover them, and on the other some large roofs feed one or two drums. Domestic water shortages, reported recurrent during dry seasons, could probably be completely avoided if existing catchment areas were all connected with nearby existing cisterns in such a manner that the ratios of cistern volumes and repective tributary catchment areas should be as nearly a uniform as possible.

In the outlying districts the crowns of pandanus and coconut trees are used as rain catchments, the water being led by way of a prop root or a stick from the trunks of the trees, down which it runs after being concentrated by the funnels of the upper whorls of leaves, to an oil drum. Nearly every house or small group of houses that does not have a cistern on Ine and Arno Islands has one tree rigged for a rain catchment.

The rain water contained 8 to 9 parts per million chlorides at Ine during July and August. This small quantity is undoubtedly due to the solution by the rain of salt crystals resulting from evaporation of sea spray. At times of low rainfall the salinity of the rainwater may increase somewhat. It is probably higher on the windward islands than on Ine.

GROUND-WATER

The groundwater observations made on Arno can be intelligently discussed only if they are considered in relation to the shallow geological structure, and can be understood only when some of the principles of ground-water occurrence as they relate to atoll islands are known. There follows, therefore, first a discussion of shallow geological structure, second a theoretical discussion of principles of ground-water occurrence

in atolls, and third the discussion of the Arno observations as a confirmation, evaluation and expansion of the principles.

Notes on geology pertinent to ground-water occurrence

The islands on an atoll are mere heaps of sand and boulders on the "reef platform", the top of the reef that characterizes the atoll. Their position and the character of the materials within them are determined by shape, size, and exposure of the sections of the reefs on which they are developed. J. W. Wells' report on the Coral Reefs of Arno Atoll describes (p. 4) the boulder ramparts characteristically surmounting the beaches on the ocean sides of the islands. The ocean beaches themselves, though not composed entirely of boulders like the rampart, contain a large proportion of boulders and cobbles and very little fine sand. The lagoon beaches, on the south side of the lagoon at least, are composed principally of sand, much of it very fine. Because the islands are the result of accretion of beach materials, generally on both shores, the materials appearing on the beaches on the two shores of the islands should be representative of the materials composing the islands as a whole. The permeability of the coarse ocean-beach sediments should expectably be much higher than that of the fine lagoon-beach sediments.

Wells also describes the beach rock commonly exposed along the shores. In this material, whether derived from sand or beach gravel, the original pores are very largely filled with cement so that the permeability is very low.

The small dashed lines in diagrams A and E of the accompanying figure indicate the depths at which gravel and hard rock were encountered under the sand as indicated by wells along two profiles across Ine Island. The

lower small dashed-line represents the top of well consolidated rock, either as seen in the bottom of large wells, as exposed on the surface, or as estimated from the limit to which drivepoints could be simply churned down, or the top of gravel exposed in wells or on the surface. The long dashed line represents a projection of the reef surface beneath the islands.

It will be noted that under the narrow part of the island shown in diagram A, there is no consolidated rock above the level of reef platform except on the lagoon beach where there is beach rock. This section was drawn across a canoe portage where a channel had been washed out across the island in a hurricane. The beach rock extended on surface only to the west edge of the portage and was found by probing to extend only part way across the portage, so that a few feet east of the section shown there was no beach rock. The whole section of the island except for the face of the lagoon beach and a small lagoon beach ridge or dune were composed of coarse sand and gravel.

In the wider part of the island there is apparently hard rock to two or three feet above the level of the reefs but not above mean sea level except where beach rock was formed on the ocean beach. This hard rock might represent merely boulders too large to crack with the drivepipe under most of the wells, but it was evidently a continuous layer under well B. No beach rock was exposed on the lagoon beach at this section, and there is room for only a very narrow beach rock zone at the most between the beach surface and well P.

The structure and texture are not so obvious in the underlying reef as are in the overlying sediments. It will be noted in Wells' discussion

of reef zonation (pp. 11-16) that along the south side of Arno Atoll the lagoon reefs are covered with extensive patches of sand that are absent or at least not prominent on the ocean reef. Whether the surface conditions are typical of the underlying materials depends on whether the present environments are typical of those prevailing while the reefs were being built. Unfortunately our knowledge of the history of coral reefs is so slight that there is no general agreement as to the conditions of their development. All that can be said, therefore, is that there appears to be a possibility for the development of asymmetry in the permeability of the reef itself. As will be shown in the analysis of the ground-water measurements such asymmetry apparently obtains under Ine Island.

Principles of ground-water occurrence on atoll islands

Most of the rainfall on atoll islands, all that is not caught on and evaporated from the plants and the surface of the ground, seeps quickly into the ground. A part of this seepage is held in capillary openings in the soil and remains available to shallow-rooted plants. In most regions of the world this soil water is the most important source of water for plants, which withdraw it and transpire it to the atmosphere. It is undoubtedly a very important source on atoll islands and probably the main source for many plants, but the low ground elevations probably permit other plants to obtain water also from a deeper accumulation to be discussed.

The excess beyond the capillary capacity of the soil generally filters down through the sand to a foot or so above sea level, where it joins and maintains a body of more or less fresh water saturating the

rock and sand. From this body of what may be called basal ground-water it may be lost by withdrawal and transpiration by deep-rooted plants, by withdrawal from wells, and by underground flow laterally to the shore-lines, both ocean and lagoon.

Salt water is denser than fresh water. Providing a volume of fresh water is somehow confined so that it cannot mix with the salt water, it will float on salt water, displacing the salt water just as a lump of ice or a stick would. The densities of fresh water and ocean water of usual salinity are such that approximately one unit of fresh water above the ocean water level will be supported by every 40 units below. A porous rock, partly submerged in ocean water, though it does not absolutely confine the water that saturates it, provides a restriction of flow that may reduce mixing sufficiently so that if fresh water is introduced into it, an integral body of fresh water will be maintained, floating on the salt water in the rock with its surface 1 foot above the level of the salt water for approximately every 40 feet of depth of fresh water below the salt water level. This principle, known as the Ghyben-Herzberg law after its first discoverers, applies in coastal areas, including islands, underlain by porous rocks in many parts of the world. Fresh water introduced by rainfall forms a basal fresh-ground-water layer whose depth below sea level is approximately 40 times the head or elevation of its water table above sea level.

It is a well established principle, called Darcy's law, first that the amount of ground water flowing through a sand of given cross section will be proportional to the hydraulic gradient, which, in a ground-water

body with a water-table that is not too steep, may be measured by the loss in elevation of the water table per unit distance measured in the direction of flow, and second that with the same hydraulic gradient in the same system but with sands of different sizes and degrees of compaction the amount of water flowing through a given cross section will be proportional to a factor called the permeability of the sand, which may be thought of as merely its capacity to transmit the water. Doubling the cross-sectional area, doubling the hydraulic gradient, or doubling the permeability of a system will double the rate of flow of water through it.

Disregarding the water withdrawn from wells, negligible on most atoll islands, the excess of rainwater introduced into a basal groundwater body of the Ghyben-Herzberg type over the amount of water withdrawn by plants from the body can be lost from the body only by flow to its margins at the shores. This flow can be induced only by a hydraulic gradient toward the shores, and by the Ghyben-Herzberg law the higher heads inland must be balanced by greater depths of fresh water inland. Assume for a moment that the permeability is constant and the rainfall, or rather its excess over transpiration and evaporation, is uniform both in space and time. Through the shore edges of the fresh water body all of the rainfall excess over the whole island must be flowing. Yet the head is low near the shore, and the thickness of fresh water small. By Darcy's law, the combination of high rate of flow and small cross sectional area must be balanced by a high shoreward hydraulic gradient, and rapid increase of both head and depth of fresh water inland. In sections of the island nearer to the center the head and depth of fresh water are

greater, and the amount of rainfall excess, being the part derived from the central part of the island only, is less. The hydraulic gradient must be smaller, and the rate of increase of head and fresh-water thickness inland is smaller. The fresh-water body, therefore, has a lenticular shape with a bow-shaped water table that is convex upward and with a lower, salt-water contact that is similarly but exaggeratedly convex downward.

In any island of uniform permeability the maximum head and thickness of fresh water will be greater if the rainfall is greater, smaller if the rainfall is less. If the rainfall is not uniform but varies seasonally there will be a seasonal change in the head and thickness of fresh water. Even the effects of daily variation in rainfall may cause variation in the head, although the effects of short term variations will lag behind the original variations and are not as great as the effects of long term variations of the same amount. The lag and damping are even greater in variations in the depth of fresh water than in variations in head.

In two islands of the same size and rainfall, the one with the lower permeability will have the higher head and the thicker fresh-water lens. In two islands of dissimilar size but having the same permeability and receiving the same rainfall, the larger island will have the higher head and the thicker fresh-water lens. Because of the change in shapes of the fresh water lens with change in size, the relationships of rainfall rate, island size, and permeability to the thickness of the fresh water lens are complicated and not those of direct proportionality.

The sea level, which controls the position of the fresh-water lens, is, of course, not constant but has tides. The loss of water from the

fresh ground-water lens is, therefore, controlled not by a constant base level but by a variable one; the hydraulic gradients throughout the lens and the rate of loss are, therefore, variable. As a consequence, the altitude of the ground-water table itself is variable, showing a tidal fluctuation much like the oceans but smaller and with a time lag. The lag and the degree of damping of the tide in the fresh water body are dependent on the distance from the coast, the permeability and depth of the aquifer, and the porosity of the section alternately saturated and drained. The greater the distance, the smaller the permeability and depth of aquifer, and the greater the porosity, the greater are the tidal damping and lag.

Fresh water resting upon salt water in the open will, of course, quickly mingle with the salt by diffusion and by mixing through turbulence accompanying any wave motion. In the medium of a permeable rock the rate of mingling is greatly reduced. Diffusion becomes an unimportant process, and there is no ordinary wave motion except at the extreme margins of the lens. However, the tidal movement of the lens and the alternate swelling and shrinking of the lens by increases and decreases in the rate of recharge, as compared to loss by withdrawals by plants and flow to the sea, result in raising and lowering of the salt-fresh contact. As the contact is raised, some fresh water is left in the rocks below the contact to mingle with the invading salt water, and as the contact is lowered some salt water is left above to mingle with the fresh. Consequently, the contact is not a sharp one but a gradual transition.

Where the spread of salt water into the fresh-water zone is larger than the downward component of the movement of the fresh water in response to recharge, the zone of mixture will extend clear to the top of the lens,

and if the rate of mixing is large enough or the recharge small enough, the water even at the top of the lens may be too brackish for drinking, or even for utilization by most plants. Sea water contains roughly 2 per cent chloride ions (equivalent to about 0.2% NaCl). Drinking water should preferably contain no more than 0.03 per cent chlorides and certainly no more than 0.1 per cent, or one twentieth the amount in sea water. The rate of movement of salt into and up through the fresh-water zone is dependent on the amount of climatic and tidal fluctuation of the theoretical salt water-fresh water boundary, on the vertical salt-content gradient, on the nature of the porosity (the mixing effect probably being heightened in material of variable pore size), and on the vertical component of the salt-content gradient (the transfer of salt being most rapid where the change in salt content with depth is highest). At the center of an island the tidal fluctuation is at a minimum, and the depth of fresh water is at a maximum, so that the rate of salt transfer is at a minimum, and there may be a low salt content and comparatively little change of salt content with depth near the top of the Ghyben-Herzberg lens. Near the coast the tidal range is greater in the groundwater body, and the total depth of fresh water is less, so that the salt gradient is steeper and the freshest water more brackish. At the shore the tide range is at a maximum and the depth of fresh water is at a minimum. Furthermore, at high tide there is a reverse hydraulic gradient carrying salt water into the island. Consequently all of the water emerging at the shore is brackish, and the change in salt content with depth and time is complex.

The average salinity at any point in a Ghyben-Herzberg lens in a small island is, therefore, complexed controlled by the size of the island,

the horizontal location of the point on it with reference to the coast lines and the vertical location of the point in the lens, by the average recharge (that is the average excess of rainfall over transpiration and evaporation losses) and by the variability of the recharge, by the permeability and porosity of the rocks, and by the tidal range in the surrounding water. The salinity at the point may be at a particular time greatly different from the average salinity at the point. Near the surface of the lens, except at the shore, the salinity will depend principally on the time elapsed since the last rainfalls and the magnitudes of those rainfalls in relation to the porosity and permeability. Soon after a rain the salinity will drop fairly quickly and then return gradually to a normal value which will be determined, like the salinity deeper in the lens, principally by seasonal changes of recharge, again with relation to the permeability. As has been already indicated, the salinity at the shore will be greatly influenced by the tides.

In the discussion so far, the rocks of the island have been assumed to have uniform permeability. That this assumption is unrealistic has been shown for Ine Island in the preceeding section, and the consequences of some of the expectable variability of permeability will be discussed here.

The difference in origin and texture between the reef problem and the islands on top of it constitutes perhaps the major source of a possible difference in permeability, but the permeability of each is highly variable and no offhand guess can be made as to which has the larger overall permeability. If, on the other hand, the reef platform has a considerably lower permeability than that of the sediments of the overlying island, the

Ghyben-Herzberg principle might apply so far as the depth of the fresh-water lens, but the part of the fresh-water body in the island sediments would function very nearly as if it were an independent body on an impermeable layer. The tidal response would be considerably less than if the reef platform had equal permeability, but the fluctuations of head with variations in rainfall would be much greater. There would be much less opportunity for mixing, and the ground-water would be much fresher. If, on the other hand, the reef platform were much more permeable than the island sediments the system would function very much as if it were uniformly as permeable as the reef platform.

The predominance of boulders, cobbles, and coarse sand in the ocean beach and the predominance of fine sand in the lagoon beach suggest strongly a greater permeability in the oceanward parts of the Ine Island than in the lagoonward parts. This difference may apply in other islands. The difference in wave intensity on the two sides of the reef may result in making one side of the reef platform more permeable than the other. The effects of asymmetry in the permeability of the reef platform should be much more important than those of asymmetry in the permeability of the overlying sediments. Any asymmetry in the distribution of permeabilities would result in a lower water table, a thinner fresh-water layer, a greater tidal effect, and a greater salinity on the high permeability side than on the low permeability side.

The beach rock found on both ocean and lagoon shores is much less permeable than the uncemented sediments. Where there is beach rock at the shore, either on the surface or buried under new sand, it should serve as a barrier to outflow of the fresh water. If the reef platform is permeable

the effect of this barrier should be small, but if the reef platform is impermeable the beach-rock barriers might serve almost like the sides of a tank, effectively sealing off the fresh water from the ocean and causing a high head, very little tidal effect, and low salinity.

Beach rock related to old shore lines and buried now in interior parts of the islands might make similar barriers within the islands resulting in the separation of two or more independent fresh-water bodies if the reef platform were impermeable. Such layers of beach rock might also result in the perching of thin bodies of fresh water above sea level.

Ground-water observations on Arno

The accompanying diagrams summarize the most important part of the observations on ground-water conditions on Ine Island. The ground-water conditions are shown across the island at a point east of Ine Village where it is nearly 1400 feet wide and at a point west of Ine Village where it is only a little more than 300 feet wide. The conditions can best be discussed as they confirm, evaluate and expand the previously discussed principles of ground water occurrence.

The relationship between the head and the distance from the shore-lines is shown by diagram A, a cross-section of the wide part of the island with a great vertical exaggeration. Three water-table positions are shown, the upper and lower being the tidal limits of the water table and the middle one being the mean position. Each slopes continuously toward the shorelines from a high point about a third of the way from the lagoon to the ocean shore, except where high-tide water table slopes inland for a short distance at each shore and also slopes toward the lagoon for a short distance near the center of the island. The probable

explanation for these deviations will be discussed shortly. The variation in mean head with distance from shorelines is shown with still greater vertical exaggeration by the two solid lines in diagram C. The heavier of these lines shows elevations of the mean water table for one day above long-term mean sea level. The lighter line indicates elevations of the mean water table for the same day above the mean sea level for that day. The latter line is probably more directly meaningful, because the heads may be expected to be very largely adjusted to tides of periods longer than a day.

Diagrams E and G indicate that the head at the center of the narrower part of the island is less than the head in the wide part of the island shown in diagrams A and C. Diagrams E and G do not show well the shape of the water table because there was only one measuring point in the narrow section of the island.

Diagrams B and F indicate the undistorted theoretical shapes of the Ghyben-Herzberg lenses in the cross sections of the wide and narrow parts of the island respectively. The depths of the lenses have merely been computed from the heads above mean sea level for the day on which they were measured, assuming that the heads were fully adjusted to long period tides. The lower limits shown may be regarded as the approximate levels of water half as saline as ocean water. Much of the water above these levels is too salty for humans or even plants to use.

That there is a greater effective permeability on the ocean side of at least the wide part of the island is indicated definitely by the relatively low head inland from the ocean shore and relatively high head inland from the lagoon shore as shown in diagrams A and C. The same asymmetry

in permeability probably exists in the narrow section too, but cannot be proved with only the one central measuring station.

The difference in permeability is also indicated by the greater damping and lag of the tides as they move in from the lagoon shore than as they move in from the ocean shore. In the tidal graphs, diagrams D and H, the damping and lag of the two principal tidal components, semi-diurnal and diurnal, are shown separately. Consideration of the tide as a whole would result in confusion, because the periods of the components are effective as well as the characteristics of the aquifer in determining the damping and lag, and the two components do not, therefore, behave as a unit as they move into the aquifer. The quantity a/x is a parameter describing the tidal progression as a whole and the values plotted were averaged from values obtained from both phase lag and damping effects in both semi-diurnal and diurnal components.

Attention has already been called to the landward slopes of the near-shore parts of the water table at high tide. Such a reversal of slope is expectable in most Ghyben-Herzberg lenses discharging without restraint to the sea. Because of the large range of the tide at line as compared to the maximum head the ocean and lagoon levels are actually nearly three feet higher than the highest part of the ground-water table at high tide. Because of the lag in the inland progression of the tide, the two lines representing the high- and low-tide limits of the water table do not represent two respectively contemporaneous positions of the water table. At times of high tide in the ocean the tide in the ground-water body is still rising toward the high-tide limit shown, and the landward slope is even more extreme than is shown. The lagoonward slope of the high-tide water

table near the center of the island probably results from the ground-water in the high permeability, oceanward part of the island acting itself like the sea in controlling the discharge of the ground-water from the low-permeability, lagoonward part of the island. This behavior suggests a rather sharp discontinuity in the permeability near the center of the island.

As a result of the lower head and greater tidal fluctuation in the oceanward part of the island than in the lagoonward part, the water at the top of the lens is freshest in the lagoonward part of the island, as shown by the dashed line in diagram C which represents the salinity of samples drawn nearly simultaneously from the several wells across the wide part of the island and plotted on a logarithmic scale. The water in well S contained 8 ppm. chlorides, the same concentration as in the original rainwater, and an amount astonishingly low to anyone accustomed to the range in salinities to be found at far greater distances from the sea in the Ghyben-Herzberg lenses of volcanic islands like Hawaii. Water of 250 ppm. chlorides or less could be found within 70 feet of the lagoon shore but not closer than 750 feet from the ocean shore, and water of 1000 ppm. chlorides within 60 feet of the ^{lagoon} shore but not closer than 400 feet of the ocean shore. The salinity at the center of the narrow part of the island at the same time was 5500 ppm. as shown in diagram G, indicating the very great importance of the width of the island on the minimum salinity in the Ghyben-Herzberg lens.

The permeability of the near-surface sediments may be estimated from the hydraulics of the shallow wells and from the characteristics of the material, that of the zone occupied by the Ghyben-Herzberg lens may be estimated from the gradients of the water table, and that of the much deeper

zone affected by tidal flow from the tidal lag and damping. The theories linking permeability with these various measurable effects are, unfortunately, poorly worked out, but the rough approximations possible provide some very useful results. The water-table gradients on the two sides of Ine Island indicate an effective permeability ten times or more greater in the zone occupied by the Ghyben-Herzberg lens on the ocean side than on the lagoon side. The permeability coefficients computed for this zone are much greater than those expected in the kinds of sediments found near the water-table, indicating that the reef platform must be a permeability discontinuity below which the permeability is greater than above. The tidal effects indicate that the high permeability continues to a depth greater than that of the Ghyben-Herzberg lens.

These observations, with a number of scattered observations of tidal fluctuation, salinity, and hardness of water not fully worked up yet, indicate that on the wide parts of the islands of Arno Atoll, and probably on wide atoll islands with a similar climate generally, there is a well developed Ghyben-Herzberg lens with a maximum head of about a foot above mean sea level containing fresh water in its upper part. The highest head and freshest water is to be found toward the side of the island under which the average permeability is lowest, which on Ine and Arno at least, and probably very commonly, is the lagoon side. Toward the ocean side the lower head and a greater tidal fluctuation result in greater mixing of the fresh water with the underlying salt water.

Seasonal changes in ground-water

The field observations on Ine were all made during the rainy season in the Marshalls. The heads measured should, therefore, be expected to be

near the maximum to be found during the year, and the salinities measured, therefore, near the minimum. It seems certain that the patterns of head and salinity differences over the width of an island will not differ significantly at any season from that noted, but the amount of decrease in head and of increase in salinity cannot at present be predicted. Monthly measurements of head in a key well are being maintained through a year by the scribe of Ine, so that considerably more information will be available on this point. The data received so far will not be listed here, because they have not yet been corrected for tidal effects and are useless until so corrected.

Native reports indicate that the salt content at the freshest wells on Ine and Bikarij rises enough to be noticeable but not enough to make domestic use of the water impossible.

Utilization of ground-water

The Marshallese draw directly only a small quantity of ground-water. There are no wells in the densely populated part of Ine Village, and the whole water supply there comes from rain catchment. In the more rural areas of both Ine and Arno there are a number of dug wells used almost entirely to supply water for washing clothes. Even where there are wells, the water used for other purposes is rain water. In view of the probable ease of biological contamination of the ground water under such a low, previous terrain, the failure to use much ground water for drinking is probably fortunate. Two of these wells sunk in comparatively high ground were lined with blocks of beach rock. Most were sunk in low places and lined with oil drums with the ends cut out, two oil drums, one on top of another, being used in some. Oil drum wells were seen also on Bikarij by Squires. None of the wells extend more than a couple of feet into the water.

Besides the wells used for wash water there are a number of pits excavated to a foot or two below the water table for use in retting coconut husks. The husks of copra nuts are merely piled in these pits, covered with leaves and trash, and allowed to decompose for a few months, after which the fibers are easily separated for use in making cordage. There is apparently no important salinity control on the retting process, some of the retting being done in pits excavated in the beaches or merely in piles covered with rocks on the beaches. The retting pits in the interior of the islands are apparently located there merely to be convenient to the source of nuts.

The small direct draft of ground-water is no indication of the overall importance of the water that seeps into the ground. As has already been discussed, the water in the unsaturated part of the soil is probably primarily responsible for supporting the heavy vegetation of wet atolls like Arno, but some of the plants are wholly or partly dependent on ground-water from the saturated zone.

Conscious use is made of ground-water in taro culture by the Marshallese. The wet-land forms of taro will grow only in soils saturated with water, and also, it is believed in Hawaii, only where the water is in movement. With no surface streams, the Marshallese have been able to meet the requirements by excavating pits from the surface of the ground 5 or 6 feet or more deep, penetrating the water-table. Taro is grown in organic muck, accumulated by rotting vegetation in these pits. The surface of the muck is generally at about mean water-table, so that water stands in the pits about half the time. The tidal fluctuation of the water-table apparently induces sufficient movement of the water. The area

occupied by taro pits on Ine Island corresponds to the distribution of the freshest ground-water in the lens, that containing 20 ppm. or less of chlorides at the time of sampling. The taro pits on Arno Island occupy a corresponding position, undoubtedly because of the same control. Taro is known in Hawaii to be rather intolerant of salt.

Ground-water apparently plays an additional important part in sustaining breadfruit trees. Breadfruit is not generally regarded as a phreatophyte (plant utilizing ground-water from below the water-table) and on high islands it is clearly not a phreatophyte. However, the distribution of productive breadfruit trees corresponds so closely with the pattern of salinity of the ground water that some ground-water control seems certainly effective. It is possible that the control is exercised only during the dry season when vadose water (that held in the unsaturated soil above the water-table) is inadequate to maintain growth, or itself reflects the salinity of the underlying ground water due to capillary rise. In general, the breadfruit trees are limited to a zone including the taro pit zone and extending beyond to a position corresponding to perhaps 200 to 400 ppm. chloride content in the underlying water at the time of sampling. There are a few breadfruit trees growing on Ine Island seaward of this limit, and a few on Arno that probably are also. None of these seaward trees are as large as many of the trees in the center and lagoonward parts of the islands, and it is noted by the Marshallese that they fail to bear or are at best poor bearers. There are no breadfruit trees on narrow parts of the islands. It should be remembered that the limits of a few tens of parts per million chlorides for taro and a few hundreds for breadfruit are wet-season limits. Undoubtedly the dry-season limits representing the real control are considerably higher.

The distribution of settlements and roads, close to the lagoon shore on nearly all of the islands of Arno Atoll, is probably very closely the result of the breadfruit and taro distribution.

Banana and papaya trees show distributions similar to that of taro, but more limited, probably as a result of limiting plantings close to settlements. No other economically important plants seem to be limited by the availability of fresh ground-water.

APPENDIX

Rainfall measurements on Arno Atoll

1950

day	July			August			Sept.	Oct.	Nov.
	Ine	Arno	Bikarij	Ine	Arno	Bikarij	Ine	Ine	Ine
1				0.50	-	-	0.44	0.54	0.77
2				1.60	1.30	-	1.17	tr	0.07
3				2.52	0.91	-	0.11	0.50	0.40
4				0.58	tr	-	?	0.51	0.39
5				0.00	0.81	-	0.82	0.55	4.56
6				0.57	0.17	-	2.40	1.25	0.45
7				tr	0.35	-	2.10	0.05	0.01
8				0.27	0.09	-	0.55	1.90	tr
9				0.37	2.26	-	1.66	0.24	0.03
10				0.66	0.21	-	0.34	1.17	0.64
11	0.07			0.10	0.18	-	0.89	0.87	0.48
12	0.35			0.91	0.93	-	0.27	tr	0.00
13	0.32			0.30	0.02	-	0.01	0.00	0.00
14	0.17		0.30	1.26	tr	-	0.02	0.00	0.00
15	0.03		0.23	1.21	0.68	-	1.16	0.14	tr
16	0.23		0.11	0.81		-	0.31	0.47	0.00
17	0.43		0.92	0.06		-	0.17	0.00	0.31
18	1.77		-	0.80		-	0.50	0.02	0.08
19	1.24		-	0.27		-	2.77	0.08	0.23
20	0.77		-	0.12		-	0.23	1.10	0.61
21	1.01		-	0.31		-	0.57	0.54	0.25
22	tr		-	0.03		-	0.59	0.09	0.00
23	tr	0.07	-	0.18		-	0.07	0.61	0.00
24	0.39	0.78	-	0.22		-	0.01	2.07	0.12
25	1.36	0.98	-	0.87		-	0.01	0.44	1.88
26	2.42	1.24	-	0.27		-	0.48	0.10	0.49
27	0.47	0.41	-	0.19		-	0.57	0.02	0.54
28	0.50	1.81	-	0.09		-	tr	2.11	0.03
29	0.00	0.66	-	0.55		-	0.00	0.61	0.14
30	0.00	-	-	4.14		-	0.14	0.91	0.00
31	0.03	-	-	0.59		overflowing		0.64	
Total	11.56 ^a	6.05 ^a	1.56 ^a	20.35	7.91 ^a		18.36	17.53	12.49
	17.10 ^b								
Mean	0.55			0.66			0.61	0.57	0.42

tr Trace

- Not read. Rainfall included in succeeding reading.

? No record. May be incorporated in succeeding days' catch.

a Incomplete.

b Estimate based on partial record.

Bench Marks at Ine Village

Bench mark 1:

The top of head of galvanized spike driven into north side of coconut palm tree about one foot above ground. Tree is nearest to ocean on southeast side of trail leading to beach from point on main trail about 75 feet northwest of northwesternmost houses of Ine Village, and about 450 feet northwest of main trail intersection at church.

Elevation: 8.71 feet above mean sea level at Ocean.

Bench mark 2:

A small cowrie shell filled with cement and set into top of unused concrete foundation post on south corner of concrete platform around house on north corner at trail intersection at church.

Elevation: 8.27 feet above mean sea level at Ocean.

Bench mark 3:

A circle chiseled in beach sandstone on lagoon beach at foot of trail leading lagoonward from church.

Elevation: 4.39 feet above mean sea level at Ocean.

Bench mark 4:

A circle chiseled on edge of east corner of concrete cistern, 30 feet northwest of trail from church to lagoon a point 125 feet from intersection at church.

Elevation: 6.74 feet above mean sea level at Ocean.

Bench mark 5:

A circle chiseled in south corner of concrete foundation of northwest concrete post at entrance to Ine Council House.

Elevation: 8.80 feet above mean sea level at Ocean.

Bench mark 6:

A circle chiseled in northwest side of concrete sill around Iroi Well, about 140 feet south of main trail at point 75 feet southeast of Council House.

Elevation: 8.14 feet above mean sea level at Ocean.

Bench marks established July 1950. Mean low water elevations and reduction to mean sea level at ocean computed by U. S. Coast and Geodetic Survey.

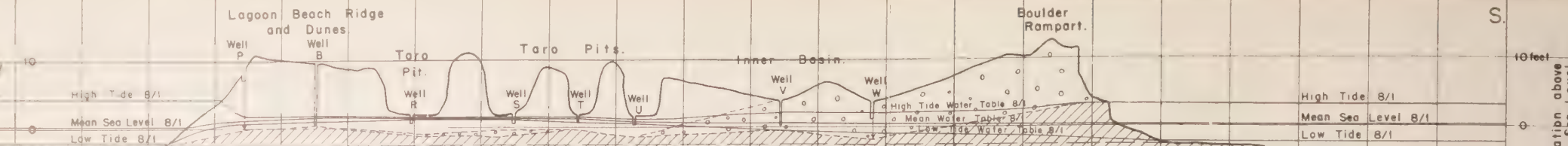
Tidal data for Ine Island

All elevations referred to mean sea level in ocean.

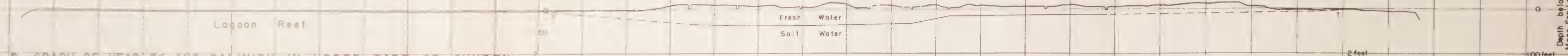
	At ocean	At lagoon
Mean high water	1.90	1.93
Half tide level	0.00	-0.02
Mean sea level	0.00	----
Mean low water	-1.90	-1.97
Mean low water springs	-2.75	-2.82

Mean low water elevations and reduction to mean sea level at ocean computed by U. S. Coast and Geodetic Survey.

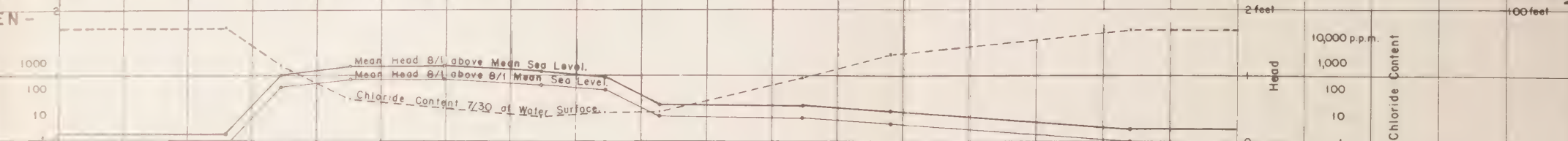
A. CROSS SECTION OF WIDE PART OF THE ISLAND SHOWING SHALLOW GEOLOGIC AND HYDROLOGIC CONDITIONS. VERTICAL EXAGGERATION 10X.



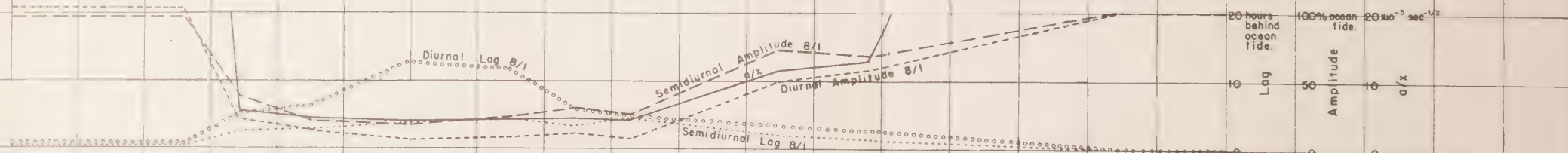
B. CROSS SECTION OF WIDE PART OF THE ISLAND SHOWING TOTAL DEPTH OF GHYBEN-HERZBERG LENS. TRUE SCALE.



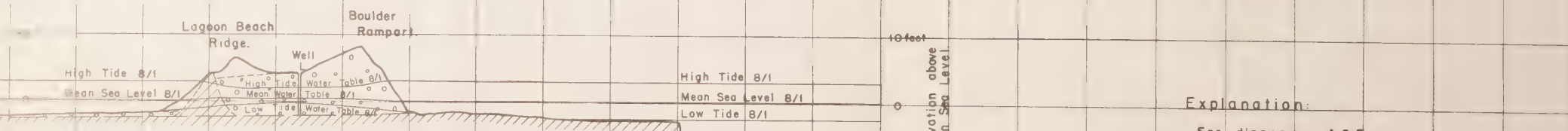
C. GRAPH OF HEAD OF AND SALINITY IN UPPER PART OF GHYBEN-HERZBERG LENS IN WIDE PART OF THE ISLAND.



D. GRAPH OF TIDAL FLUCTUATION IN GHYBEN-HERZBERG LENS IN WIDE PART OF THE ISLAND.



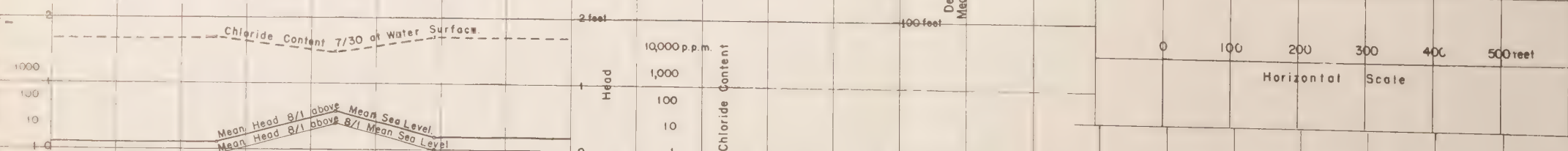
E. CROSS SECTION OF NARROW PART OF THE ISLAND SHOWING SHALLOW GEOLOGIC AND HYDROLOGIC CONDITIONS. VERTICAL EXAGGERATION 10X.



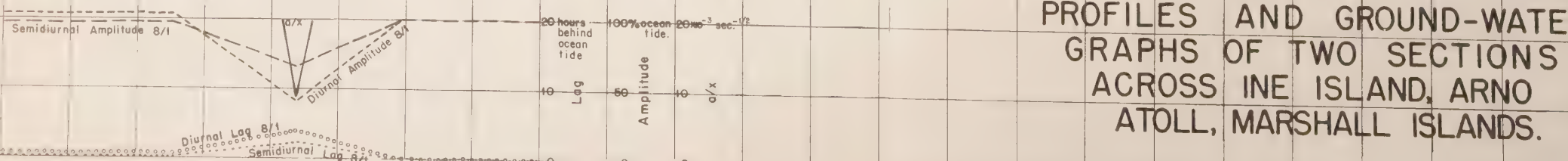
F. CROSS SECTION OF NARROW PART OF THE ISLAND SHOWING TOTAL DEPTH OF GHYBEN-HERZBERG LENS. TRUE SCALE.



G. GRAPH OF HEAD OF AND SALINITY IN UPPER PART OF GHYBEN-HERZBERG LENS IN NARROW PART OF THE ISLAND.



H. GRAPH OF TIDAL FLUCTUATION IN GHYBEN-HERZBERG LENS IN NARROW PART OF THE ISLAND.



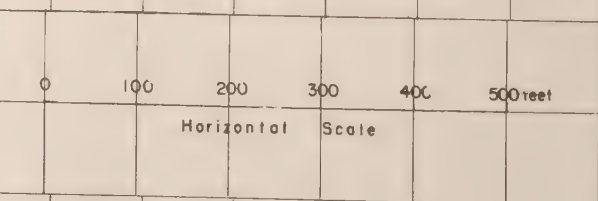
Explanation:

For diagrams A & E.

Unconsolidated sand.

Boulders or cobbles with or without sand, or partly consolidated sediments.

Reef rock or beach rock.



PROFILES AND GROUND-WATER GRAPHS OF TWO SECTIONS ACROSS THE ISLAND, ARNO ATOLL, MARSHALL ISLANDS.

ATOLL RESEARCH BULLETIN

9. The Coral Reefs of Arno Atoll, Marshall Islands

Issued by

THE PACIFIC SCIENCE BOARD

National Academy of Sciences - National Research Council

Washington, D. C.

December 15, 1951

THE CORAL REEFS OF ARNO ATOLL,
MARSHALL ISLANDS

SCIENTIFIC INVESTIGATIONS IN MICRONESIA - Pacific Science Board

#

An atoll has a top that's flat
And featureless extremely.
Corals and algae make a mat
Where mountains are not seemly.

(R.H.F., 1949)

John W. Wells
Cornell University
December 1951

ACKNOWLEDGMENTS

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To all of the above who helped to make possible the research described in this report I wish to express my gratitude and appreciation.

Special thanks are due to Mr. Donald F. Squires (Cornell '50) without whose able assistance in the field much less would have been accomplished.

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I. Field Work

A. Reefs

The coral reefs were the main object of study during the field period, and all types of reefs represented at Arno were investigated in more or less detail:

Ine Island - Seaward-leeward reef; windward-lagoon reef. A three-mile stretch on either side of Ine Village was mapped in detail on a scale of 1:8000.

Takleb Island - Seaward-windward reef; leeward-lagoon reef. Mapped.

Aotle and associated islets - Seaward-windward reef; lagoon reef. Mapped.

East Horn (Malel to Lonar I.) - Seaward-windward reef; lagoon reef (enclosed lagoon). Mapped.

North Horn (Eneman-Bikarej-Namwi) - Seaward-windward reef; seaward-leeward reef; enclosed lagoon reef; reef "dam" at north end. Mapped.

Studies were made of the water temperature fluctuations on the reef tract on the seaward side of Ine Village.

B. Lagoon

Following the arrival on 19 July of dredging gear from Washington, dredging was carried out nearly every day until 1 August, when the gear was re-packed for shipment. Earlier attempts to dredge with a crude dredge made from material at hand produced results, but were less than satisfactory. The regular dredges were more successful, but the great difficulties in operating from sailing outrigger canoes emphasize that systematic dredging, a necessary part of any scientific study of an atoll, is possible only from a sizeable powered boat. Nevertheless, as a result of Mr. Squires' persistence, a number of bottom samples and zoological specimens were obtained from some 25 hauls in the lagoon, even though nearly half of them were dry runs.

C. Collections

Corals. About 600 specimens, mostly cured, of reef and lagoon corals were collected.

Other. Insofar as possible, with only 2 gallons of alcohol, specimens of mollusca, echinoderms, alcyonarians, foraminifera, crustaceans, etc., were collected for the U.S. National Museum, as well as some dried material. A number of specimens were preserved but later had to be discarded or dried because of lack of sufficient preservative. Ten gallons of alcohol requested from Majuro late in June was finally delivered at Majuro on the return journey.

Some was added to the one tank, but the rest by that time was of no use and was returned.

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In all/wooden packing cases were filled, weighing about 1000 pounds and shipped back by surface transport. The corals are still being studied, and a complete list at this time is impractical, but it is estimated that over 100 species representing about 45 genera of scleractinian and hydrozoan corals were procured, with ecological data. A list of these genera is appended.

About 350 photographs (Kodachrome) were taken, mostly of reef phenomena, including a number of underwater views. Five hundred feet of 16-mm. color motion picture film were exposed, again mostly of reef features above and below water, with unexpectedly good results. The motion picture camera and tripod were a loan from the Navy through the Honolulu office of the Pacific Science Board, and grateful acknowledgment of this is here made.

II. Structure and Physical Processes

A. General Statement

Arno Atoll, in the southern Marshall Islands at approximately 172 deg. E. and 7 deg. N., lies in the northeast trade wind belt and in the north equatorial current. The latter is deflected northwards during the summer months by the equatorial counter current. It is in that part of the Pacific where the surface water temperatures do not fluctuate more than 1 deg. above or below 28 deg. C. - the warmest part of the Pacific. The temperature, clarity, and agitation of the surface are at the optimum for reef coral development, but the planktonic food supply, on the other hand, despite the seasonal reversal of oceanic currents, is lower than in areas farther to the south west and coral growth is below the maximum.

Arno, like many atolls, departs from the common idea of circular atoll shape, being roughly rectangular with two extensions or "horns", one extending to the north about 5 miles from the north corner of the rectangle ("North Horn"). The other extends about 7 miles northeastward from the east corner ("East Horn") (Figs. 1 and 2). Both horns are peculiar in that each encloses near its tip a small secondary lagoon separated from the main atoll lagoon. The total area enclosed by the seaward reefs and lagoons is about 147 sq. mi. The surface reefs cover about 16 sq. mi. and on them 133 islands and islets form about 5 sq. mi. of dry land. The main lagoon encloses about 125 sq. mi., the secondary lagoon in the East Horn about 4.5 sq. mi., while the little enclosed lagoon of the North Horn has an area of only 1.5 sq. mi. (Fig. 4). The seaward reefs extend continuously around the entire atoll, except where they are broken by Tutu and Takleb Passes, which have threshold depths (15-25 fms.) nearly equal to the lagoon depth, three shallow (4 fms or less) passes east from Takleb and one shallow pass into the northwest part of the East Horn lagoon. The total peripheral extent of the seaward reefs is about 65 miles, and except for minor pass into the East Horn lagoon, all breaks in the reef are in the 6-mile windward stretch of the northeastern face of the atoll extending southeasterly from Tutu Pass toward Namej Island.

The seaward slopes (Fig. 3) of the outer reefs are steeper to leeward than to windward. No precise data are available, but it is obvious from an inspection of aerial photographs of Arno, and indicated by H.O. Chart 6005, that there is a decided difference. At Ine Anchorage a depth of 200 meters is reached about 150 meters out from the reef margin, a slope of 55 deg. At 1700 meters the depth is 1000 meters, about 27 deg. Thus the profile from reef edge seaward is concave and steeper near the reefs, and gentler with increasing depth. On the seaward side to windward off Takleb Island the depth 400 meters out from the reef edge is only 40 meters, a 7 deg. slope. In the next 350 meters the depth increases to 200 meters, a slope of 25 deg., nearly the same as the downward slope from 200 meters on the leeward side. At 3500 meters from the reef margin a depth of 1000 meters is reached, a slope of 19 deg. from 750 meters. This slope is essentially convex near the reefs, thence gently concave. The presence or absence of a 10-fathom terrace like that at Bikini is not determined, but comparison of aerial photographs of corresponding parts of the two atolls suggests strongly that it is developed on the windward side of Arno.

The material of which the reef and islands of Arno is composed is wholly coral reef limestone and its derivatives: boulders, cobbles, pebbles, sand, and finer silt-size particles. Small patches of phosphatic limestone occur in the interior of a few of the larger islands, but rock material other than limestone is very rare and accidental. Early in the 19th Century Chamisso noted that the natives in the Radack chain (eastern Marshalls) searched the beaches for stranded tree trunks with tough rocks tangled in their roots, for tools. Stranded trunks from North America are actually not uncommon on the Arno beaches, presumably carried in by the California and North Equatorial Currents. Two in particular were noted in 1950, one a huge cut fir log 5 x 55 feet, the other a redwood trunk in the roots of which were several sizeable chunks of a tough quartzitic grey-green sandstone. The only other stray "foreign" rocks on Arno are bits of pumice ranging in size from small pebbles to rounded pieces the size of one's head, found both high on seaward and lagoon beaches and inland.

B. Structure of the atoll islands. (Fig. 5).

The beaches of the seaward sides of the atoll are everywhere bordered, with very few exceptions such as Ine Anchorage and stretches of low reef tract on which islands are not yet developed, by boulder ramparts. These are ridges of boulders and cobbles of water-worn coral carried by storm waves from the outer slope and ridge of the reef over the reef flat. The rampart is 6 or 7 feet high on leeward sides of the atoll, but to windward it is often as much as 10 or 12 feet.

Boulder ramparts or ridges are the first stage in the development of islands. In their lee accumulate finer materials, stray boulders, pebbles and sand, carried over the ramparts and around their crescentiform ends, spread out on a gentle slope toward the lagoon. Where the rampart is fairly stable, chinks between the larger pieces become filled in with sand and pebbles from the beach zone, and between tide-marks it may be consolidated by cementation into solid strata of beach conglomerate with initial dip toward the reef flat to which it is welded. Beach conglomerate is often exposed where a slight shift in wave approach removes loose surface material and stands with the

rampart as the second line of defence behind the reef margin.

Where the seaward reef flat is broad the inner part near shore may be covered by a rubble tract or sheet of large irregular coral blocks to a thickness of as much as 3 or 4 feet. Since they lie between tide marks, these sheets may here and there be consolidated into a tough horizontal stratum. All gradations from fresh, more or less angular rubble through rubble conglomerate to old conglomerate, corroded and decayed to the point of being mere remnants more or less stoutly welded to the reef flat, can be seen.

The beaches around islands are relatively narrow, 3 to 4 feet high, and lie between low tide level and the highest point ordinarily reached by the waves at high tide. Their slope is adjusted to the normal wave action in their area. On seaward side of islands they are steep and narrow, with slopes up to 20° . On lagoon sides they are wider with slopes of 5° - 10° . A few inches beneath the surfaces of most sand beaches bordering the lagoon are patches of beach sandstone with initial dip corresponding to the beach slope, developed as a result of cementation between tide marks, and often welded by their lower edges to the reef flat. Beach sandstone, like beach conglomerate, is an important factor in anchoring islands to the reef.

Another structural feature is the sand dunes developed on the lagoon sides of some islands where there is a sand beach facing the wind. The strong trades sweep over the beaches exposed at low tide and move particles of sand 0.2-0.7 mm. in size up the beach and drop them at the top, in much the same manner as dunes are built on other windward shores elsewhere. The dune sand is composed of more uniformly-sized particles than beach sand. The dunes form more or less continuous ridges 2 to 5 feet above the top of the beach. Behind them the island surface slopes gently toward the interior of the island where the wind-carried sand mingles with the material spread in the opposite direction from the boulder rampart. Such a dune ridge extends almost continuously the length of Ine Island. In places it is double, the outer one being lower and newer than the inner one. At one point, about a mile east of Ine Village, the ridge is nearly 15 feet above the beach (Arno's mountain) and 50-100 feet broad.

The interiors of islands are 6 or 7 feet above low tide level, and consist of more or less horizontal layers of material derived from the seaward boulder rampart and lagoonward dune ridge or beach, often more or less consolidated into island or cay sandstone.

Figure 5 shows a generalized cross-section of an island on the lee side of Arno Atoll.

In summary: the islands and islets represent constructional work of wind and wave with materials derived from the living reefs. They are accumulations of loose material partly held together by a patchwork "endoskeleton" or framework of beach conglomerate to seaward, beach sandstone lagoonward, and interior island sandstone. They are seen in all stages of development on Arno, from lonely little bits of rampart with a single sprouting coconut to broad islands sufficiently old to have small patches of phosphatic limestone in their interiors. They are not, at least on Arno, as some would have us believe, the remains of old reef flats raised above sea-level by the more or less recent 5 or 6-foot lowering of sea-level coincident with the accumulation of the Greenland and Antarctic ice-caps. Evidence of this eustatic shift is supposed to be widespread in the Pacific but no features at Arno need be ascribed to it. Speculation that the

old reef surface elevated by eustatic change has been completely planed away at Arno seem unnecessary. Emphasis by some observers that isolated masses of reef rock welded to the present reef flat is evidence of an older, now elevated reef flat overlooks the possibility suggested here that they are remnants of old cemented rubble tracts.

C. Surface processes and changes.

Everywhere on Arno evidence can be seen of moderate change due to shore-line processes, and here and there vast changes due to occasional great typhoons. The former are more obvious on the lagoon side, the latter on both lagoon and seaward sides, and both are most apparent on the lee side of the atoll.

The thirteen-mile long lagoon shore of Ine Island has a nearly continuous sand beach. In places this beach is being aggraded, as at Ine Village. Some of the slow sand increment is carried in from the lagoon reef flat, and some is shifted along shore by waves from another part of the beach. From Ine Village westward for some miles stretches of gravel-cobble beach alternate with stretches of beach sand. The gravel beaches develop in places where waves are strong enough to degrade, leaving concentrations of coarse material. This alternation coincides with the alternately concave and convex parts of the reef and island with respect to the lagoon. Degradational gravel beaches occur along the salients, aggradational sand beaches in reentrants. The lagoon reef is not yet wide enough to stabilize the shoreline - the geomorphologists' Nirvana, a shoreline of equilibrium, is far from reached.

Active degradation of a sand beach is seen at the east end of Ine Island, where for the last few miles the beach is narrow and the dune ridge is strongly undercut so that turf overhangs the top of the beach. Coconut palms have toppled onto the beach in an almost even row and are slowly dying. About a quarter mile west of Ine Village, approaching a convexity in the island, undercutting has proceeded so far inland that the dune ridge has almost disappeared and a 3-foot cliff of island sandstone is now being cut into. At this site the island is unusually narrow, less than 100 feet, and the initiation of the present slow undercutting is the result of washing away of most of the dune ridge and old beach sandstone by typhoon waves. The beach sandstone that lay under the old beach is now exposed at the water's edge at low tide.

More striking, however, than the normal shoreline changes, are the effects of the typhoons that strike the Southern Marshalls four or five times a century. Records are rare and older natives are the only source of eye-witness information, but their recollections are naturally vivid of such disasters and are confirmed by the physical traces of typhoon effects which can still be seen. One old man, Lijōmmar, remembers four typhoons during his lifetime, those of 1905 and 1918 being the last two, as he related to Dr. E. L. Stone in 1950. These are remembered by others and their dates seem fairly certain. That of 1905 was the most violent.

Previous to 1905, according to Lijōmmar and others, all of the islands now scattered along the reef from the eastern tip of Ine some 18 miles to L'Angar Island at the tip of the East Horn were one continuous island, with only one canoe passage (portage?) between the west end of Ine and L'Angar, apparently

apparently a mile or so north of the present east end of Ine (Fig. 7,A). The typhoon of 1905 swept away long stretches of this island (Fig. 7,B) so that where there was a single long island there are now about 40 (Fig. 7,C), the smaller ones having been built up since the typhoon, the larger ones being remnants of the original island. Confirmation of this extensive change is found on a small chart, corrected by officers of the old "Albatross" from a German hydrographic chart, published in 1903 by Alexander Agassiz (M.C.Z. Harvard, Mem., vol. 28, fig. 4, p. 228), which shows a continuous strip of land from L'Angar to the west end of Ine, broken by a pass near the present east end of Ine and another about 5 miles west of Ine Village. If these passes existed, they must have been merely canoe passes over the reef, or possibly portages, for no break in the reef can be seen at or near these places on aerial photographs, and Agassiz himself did not see them, saying "....there are said to be several boat passes on the southwestern face of the lagoon." At any rate, two years after the corrected chart was published, it was obsolete.

The destructive effects of typhoons on atoll islands can be seen at many places on the leeward side of Arno. Mention has been made of the washing away of a stretch of lagoon beach just west of Ine Village, exposing island and beach sandstone. About 2 miles farther west beyond Jab'u, the island narrows to less than a third of its normal width and in places is scarcely 30 feet wide (Fig. 8). For half a mile the dune ridge is very much lower and between it and the boulder ridge on the other side of the island the sand seems to have been scooped out into miniature box canyons with steep heads toward the rampart. About 50 feet from the beach remnants of the old beach sandstone can be seen at low tide on the lagoon reef flat, indicating the former greater width of the island. This change was the result of water piled up on the leeward side during the 1918 typhoon washing completely over the island into the lagoon, carrying away land, dune, and lagoon beach. Since then a new beach, underlain by freshly-formed beach sandstone, and a new dune ridge have developed. Similar washouts were seen at the east end of Kilange near the base of the East Horn. On the next island west, Malel, are large numbers of prostrate breadfruit trees, still alive, which were downed by the same storm.

Eastward from Ine Village extend two old paths bordered by beach sandstone slabs, one paralleling the lagoon beach, the other swinging south and paralleling the seaward shore just inside the boulder rampart. Beyond Stony Point, as one approaches the next "point", the beach swings inward crossing the trend of the path which ends abruptly as if cut off. For several hundred yards beyond, the southern part of the island has apparently been carried away by a typhoon to the extent that on the next point the old island sandstone core is now exposed at the edge of the reef flat.

The 1905 typhoon washed away parts of the former long island between L'Angar and Ine and left long stretches between with only the bare bones of former land, -- a low ridge of beach sandstone on the lagoon side, a rubbly band in the former island interior and a new seaward boulder rampart (Fig. 6). Over the lagoon reef opposite these places are strewn masses of rubble, now corroding, the finer materials having been bypassed into the lagoon. Dark lines of old beach sandstone, marking the site of former beaches and land, show well on aerial photographs and can be traced nearly continuously between islands from L'Angar almost to Ine. The amount of land lost during this typhoon on this part of the atoll was about 160 acres, only 5% of the total land on Arno now, but nearly 25% of the area of the former island.

Typhoons and destruction of land on Arno will occur again and again. The forces tending to construct new land are slowly but steadily operating, but in the 46 years since the last great storm, they have not replaced the land lost then. It has not been possible to determine how many of the small islands in the area of major destruction are remnants and how many are replacements, but certainly less than 10% of the lost acreage has been made up. The typhoon of 1918 probably destroyed part of the gain, and that of 1950 may have washed away still more. The long narrow islands of Arno invite typhoon damage, for they act as barriers to the heightened tides and waves of the storm, and the only egress for the piled-up waters is over the land.

From these observations it would appear that the windward side of atolls in the Southern Marshalls are safer and less susceptible to damage than the leeward. Typhoons in this region come from a southerly direction and the normally leeward side bears the brunt of the shock. The leeward reef, its islands, and the lagoon absorb and weaken the rush of water, and waves in the lagoon can hardly rise as high as the open sea waves. The windward islands suffer mainly from the high winds instead of being overwhelmed by water during a great storm. Unfortunately, most of the land on Arno is on the lee or typhoon weather side.

Little, if anything, can be done directly by man to lessen, much less prevent, loss of land or soil by typhoon damage. This should be kept in mind if attempts are ever made to increase soil productivity on atoll islands. Greater soil productivity leads not necessarily to higher or better standards of living, but to larger populations. Well-intentioned attempts to improve the lot of the native populations of atolls thus might well jeopardize more lives than ever when the inevitable typhoon sweeps in, and lead to appalling drops in population and lower living standards than now obtain for the survivors. True, the Indian Ocean atoll of Cocos-Keeling has been almost completely devastated several times in the last century by typhoons and still comfortably supports a very much denser population than any Pacific atoll. But Cocos has capital wealth obtained from other sources than the atoll soil and is populated by a highly energetic group of people under a strong patriarchy.

D. Reef types.

The seaward reefs at Bikini Atoll in the Northern Marshalls were recently classified by Tracey, Ladd, and Hoffmeister (1948, G.S.A. Bull., vol. 59, p. 870), largely on the basis of the character of the reef margins, as follows:

I. Strongly grooved.

- A. Lithothamnion ridge low, uncut by grooves.
- B. Lithothamnion ridge prominent, cut by grooves.
 - 1. Room and pillar structure developed.
 - 2. Algal mounds and blowholes developed.

II. Grooves weak or absent.

- A. Margin smoothly scalloped.
- B. Margins made irregular by erosion.
(two subtypes)

The distribution of these types at Bikini is shown on Figure 3 of the paper cited. Application of this classification to the Arno reefs is shown in Figure 2 of this report. Comparison of the two shows one striking difference and a number of similarities. The difference is the almost complete absence of reefs of Type II, in which the grooves down the upper part of the slope are weak or absent, at Arno, whereas at Bikini they are characteristic of the leeward stretches. According to Tracey, Ladd, and Hoffmeister, where reefs of this type are developed there is no evidence of a terrace. At Arno there is no evidence of a terrace on the leeward slopes, but a strongly grooved, steeply sloping reef margin of Type IA, with low algal ridge, is developed. A typical profile of such a leeward reef of this type at Arno is shown in Fig. 9.

Reefs of Type IB₂, with strongly developed algal ridge, are found at corresponding windward sites at both atolls, alternating with Type IA which is developed on stretches less exposed to the northeasterly and easterly trades. At Arno there does not appear to be the close relation between islands and Type IB reefs and stretches between islands and Type IA, observed at Bikini. In areas where there are islands or islets on the reef, open spaces between islands are narrow and water flow across the flat is impeded by rubble.

At only one site at Arno is a reef of Type II (grooves weak or absent) developed. A stretch of about 300 meters northwestward from Stony Point on the seaward leeward side at Ine Anchorage in a shallow bay between two crescentiform swellings of Ine Island best fits Type IIA. Grooves are absent and the margin slopes very steeply, practically vertically at first, less so below about 10 meters, with an average slope of 55 deg. to 200 meters. There are more or less regular re-entrants 3 to 10 meters deep, 2 to 10 meters wide, with sandy or rocky floors. One or two of these are interconnected by open channels, isolating flat-topped pillars, but there is no evidence of collapse due to erosion. Wind waves are negligible at this site and the strong swells from the east are reduced by the projection of Stony Point.

E. Lagoon Reefs

The lagoon reefs are not so continuously developed as the seaward reefs although banks on which reefs might exist are continuous. They are best developed along the windward lagoon side of the west, south, and north sides, where there is little or no wash of sand and other detritus from the seaward reefs. The only development of leeward lagoon reefs on the windward side of the atoll is in the vicinity of the two threshold passes, Tutu and Takleḃ. The sand banks developed on the lagoon side of the windward reefs from wash from these reefs are rapidly extending into the lagoon. They slope steeply downward toward the lagoon floor at about 35 deg., the normal angle of repose.

In the enclosed lagoons of the North and East Horns the reefs are distributed as in the main lagoon but again coral growth is patchy owing to the sand cover of the flats and lagoon slopes.

In the North Horn (Fig. 4), which has no pass whatever to seaward a special situation has developed. On all sides except the north, the seaward reef flats are built up either with islands or thick rubble to a level above low tide level. On the eastern side the rubble areas between islands are penetrated by sand-floored channels from the lagoon side, usually with a moderately rich growth of corals, but about halfway to the seaward margin they become very shoal and choked

by rubble which often is more or less cemented. Except to the north this rim is 1 to 2 feet above low tide level, but is 2 to 3 feet below high tide level. When tide level falls below the rim level the excess water flows northward and part of it escapes over the lower rim between the ends of the windward and leeward reefs. The rest of it flows outward through the channels onto the seaward reef flats. Formerly most of the excess flowed out by the northern outlet, which was covered or crossed by a reef flat built to within about a foot of low tide level. This rapidly moving water, however, supported a profuse growth of corals and calcareous algae which have now grown up across the opening, forming a low, broad, convex rampart, one edge of which slopes steeply into the lagoon, the other gently down into the scattered microatolls around the embayment in the northern end of the horn. At present this dam has a uniform crest of at least 2 feet above low tide level on the seaward side, and over its entire surface there is a steady but diminishing outflow of water as the tide ebbs. Coral growth is rich but the depth of water on the spillway slope at each low tide is now hardly more than an inch and broad stretches are exposed, and coral colonies are low and spreading. Thus the water level in the enclosed North Horn lagoon never falls as low as the level reached at low tide on the seaward reefs.

This enclosed North Horn lagoon is much shallower than the main lagoon or the enclosed East Horn lagoon, and soundings shown on the H.O. chart indicate a maximum depth of 10 fathoms. Coral knolls are numerous, and the lagoon is probably filling rather rapidly. Because of the absence of even a shallow pass into this lagoon circulation of the lower levels of water in it must be restricted, but unfortunately it was not possible to obtain bottom samples bearing on this point.

F. Coral Knolls.

These characteristic structures of atoll lagoons, often loosely referred to as "coral heads", are abundant in all the Arno lagoons (Figure 1 shows only a very few of the knolls). Some of them are sufficiently developed as to be awash or even exposed 2 to 4 feet at low tide. In the main lagoon there are six areas where they are concentrated: 1) in the area at the base of the North Horn generally west of Eneweto Island, 2) a large cluster fanning out from the break in the reef south of Jarkul Island, 3) across the inner end of Tutu Pass, 4) halfway across the lagoon between Takleb Pass and Ine Village, 5) in the southeast corner of the lagoon, and 6) in the secondary embayment at the base of the East Horn.

The distribution of the knoll clusters seems less than fortuitous. Three are in corners of the lagoon, and two are associated with threshold passes. The remaining one, the large Jarkul cluster, is probably also of the second group. The broad break in the reef southeast of Jarkul (2 miles northwest of Tutu I.) suggests a filled-in threshold pass. The absence of a strong seaward reef at this point still enables the wind waves and swells to sweep in and transport large quantities of sand which are building a "delta" into the lagoon over the site of the former pass. Around this "delta", within a radius of about 1.25 miles there are at least 65 knolls visible on aerial photographs in addition to two large shoals. The cluster around Tutu Pass is smaller - 22 - and none is visible in the immediate vicinity of Takleb Pass. The latter is shallower than Tutu and less to windward, but the large cluster in the lagoon to the south, beginning about a mile from the pass, may be related to it. Are these knoll clusters related to the developmental stage of the passes with which they are associated?

A somewhat similar distribution of knolls may be found in the lagoon of Majuro Atoll, suggesting an interesting minor research problem.

III. Reef Zonation

A. Seaward Reefs

As indicated above, three reef types of the Tracey-Ladd-Hoffmeister classification are developed at Arno: IA, IB, and IIA.

1. Type IA.

This is the dominant type at Arno, and extends almost uninterruptedly from the west side of the North Horn southward around the lee side of the atoll to the eastern end of the East Horn. A typical section of this type of reef, strongly grooved with a low algal ridge uncut by the grooves, is shown in Figure 9. The broad rock flat, seemingly barren, supports no coral growth except in occasional depressions where small patches of Porites lichen and a few other forms grow feebly. At practically all sites, however, except on open stretches unbroken by development of islands (i.e., NE of Kilomon, E. of Takleb), there is an extensive overgrowth of a curly, disreputable-looking brown alga (Microkamura) on the fronds of which live vast numbers of Calcarina. Associated with these are many individuals of the large, closely-adherent pelecypod Chama which resemble projections of rock about the size of one's fist. This is the Calcarina-Chama zone. This zone is truly barren only where there are prominent convexities in the reef (Fig. 8). Where this flat begins to slope gently down as the "algal ridge" toward the upper ends of the grooves, low and broadly adherent colonies of Pocillopora are usually dominant, (with fewer specimens of Acropora, Astreopora, Porites, etc.), on the weak encrustation of lithothamnion, - the Pocillopora zone, at the outer end of the waves of translation at low tide. Beyond this, in the surf zone, Pocillopora is replaced by Acropora (A. pectinata, A. digitifera, etc.), forming a zone extending well down into the upper part of the grooved area. Other common genera in the Acropora zone are: Astreopora, Porites, Millepora, Favites, etc.

2. Type IB.

This seaward reef type, with relatively high, prominent algal ridge, is characteristic of the exposed windward reef tracts, and is replaced by Type IA only where some protection is afforded by concavities in the reef margin. The usual zonation of this type is shown in the section, Figure 10. The rocky flat is usually less richly endowed with the alga-Calcarina-Chama association and the ridge is not a place of vigorous coral growth. The surge channels are usually shallow, rarely roofed over, and often partly filled with coarse boulders. Occasional small colonies of Acropora cuneata are found, but less commonly than in the corresponding zone on reefs of this type at Bikini. Nowhere is this reef as broad as at Bikini, and no trace of an inner Heliopora zone was noted.

3. Type IIA.

As previously noted, this type is found only in a limited area at Ine Anchorage (Fig. 8). It is distinctly zoned by corals as shown in the section, Figure 11. Following an inner barren zone, exposed for long periods at practical

every low tide, is a broad tract thickly settled by extensive colonies of Montipora ramosa, -- a nearly exclusive society, here and there replaced by patches of Acropora hebes or alcyoniid "soft corals" (Lobularia). Occasional colonies of Synaraea, Leptastrea, Porites (especially P. superfusa), and Pavona, also occur. At low tide the depth is from zero to about fifteen inches, and the water is practically undisturbed by swells or waves of translation. The outer limit of this zone is at about the inner extent of the ordinary low tide waves of translation, where it is succeeded by a zone dominated by Acropora, especially species of the corymbose A. pectinata type, which extends to the reef margin. Fungia scutaria is common in this zone. It is the zone of richest variety of corals and other reef animals. Calcareous algae are relatively very unimportant. Species of at least 33 genera of scleractinians and hydrozoans have been collected in the zone, but Acropora accounts for around 90% of all colonies. Over the reef edge and in the re-entrants along the edge the next zone, marked by the pedestal colonies of A. reticulata, begins about 6 feet below low tide level in water only slightly agitated by the constant but low swells, and extends down to about 30 feet, where coral growth becomes very sparse. Fungia scutaria, F. fungites, and F. concinna are very common.

B. Lagoon Reefs

Two main types of lagoon reefs may be distinguished at Arno. One is found on the leeward side of reef tracts on the windward side of the atoll, or on the leeward side on long stretches where islands are not yet developed. The other is developed on the windward side of the island-flecked reef tract on the leeward side of the atoll.

1. Leeward Type.

The first type is developed in the enclosed lagoons of the North and East Horns (Fig. 13), and in places along the sheltered leeward side of the reef tract between the horns (Fig. 12). The immediate substratum is primarily the sand washed into the lagoon margin from the outer reefs, either across the flats or around the passes. These sand tracts slope steeply (35 deg.) at their inner edges, which may be from a very few to several hundred feet out from the shore, down to the lagoon floor. On this insecure base luxuriant coral patches are scatteringly developed, rising with more or less abrupt sides from depths of a foot or so, often very close to the beach, to 12 or 15 feet. The spaces between them are flat and floored with sand on which few corals grow. The characteristic coral of this zone is Porites andrewsi, a ramose form found in the same environment at Bikini and other northern Marshall atolls. Also common in this zone is Acropora palifera which often forms huge colonies in shallower parts of the sandy interspaces. Fungia is common. The Acropora reticulata zone, found below about 6 feet on the Type IIA seaward reef, extends as might be expected on these protected lagoon reefs well into the P. andrewsi zone, in as little as 2 or 3 feet of water at low tide. It does not appear to extend downward much below about 20 feet.

2. Windward Type

The second type of lagoon reef at Arno, exemplified by the section, Figure 14, extends from near the southeastern corner of the lagoon along the windward southern side of the lagoon the entire length of Ine Island to Arno

Island, about 13 miles, and beyond. It is the broadest of Arno reefs of any type, averaging about 1500 feet from beach to margin. The flat consists of a patchy veneer of sand and silt on an uneven, corroded reef rock flat which lies from 6 inches to 3 feet below low tide level. It is shallower near shore, deepening to about 3 feet at the midpoint, then shoaling near the margin, which in a few places is exposed at low tide. Beyond this low ridge the rock surface, often quite bare of sediment, slopes gently at about 10 deg. to the sandy floor of the lagoon at 15 or 20 fathoms. Coral growth over this type of reef is sporadic and nowhere rich and flourishing. The width and depth of the tract enable the wind waves to proceed well in toward shore where they keep the sand and silt well stirred at high tide, inhibiting the growth of all but a few colonies of such hardy forms as Porites lutea and Pocillopora damicornis. Hippopus is common in this inner zone. In the deeper water beyond and nearly to the margin, Astreopora is abundant, forming massive heads up to 5 feet across. Many large dead colonies of Acropora palifera and A. gemmifera, occasional large Pocillopora, and discouraged Porites andrewsi also occur. On the bare, pitted and irregular marginal slope is found the widest variety of forms, but no one species appears dominant. Especially common are several species of soft alcyoniid corals (Lobularia and Lobophytum). Fungia is absent. Lithothamnion is only occasional and not flourishing. From a depth of about 5 feet down the slope, Acropora reticulata is dominant, often forming huge spreading brackets 3 to 8 feet across. This zone extends nearly to the lagoon floor into the Acropora formosa habitat.

A third type of lagoon reef, with an algal ridge and zonation similar to that of seaward reefs, is developed at Bikini around the western end of the lagoon, where wind waves developed over a fetch of about 20 miles produce a strong surf. This type is not found at Arno where nowhere do prevailing winds have a fetch of more than 10 miles.

IV. Reef Temperatures

For mid-Pacific reefs there is, so far as the writer is aware, only one detailed record of water temperature variations across a definite reef tract. In 1918, A. G. Meyer published (Carnegie Inst. Wash., Pub. 213, pp. 31-34, fig.9) an account of the temperatures on the Maer Island coral reef, Torres Straits,-- a fringing reef about 188 feet wide. In general he showed that while daily temperature changes at the seaward margin have a narrow range (3.5 deg. C.), the range increases toward shore to as much as 12.5 deg. (C.), and concluded that the high temperatures experienced during part of the year must be sufficient to kill all corals within 450 feet of the shore.

During the month of June, 1950, a number of temperature traverses were made across the Ine Anchorage Reef along the section line of Fig. 11, at various times of day and states of tide. The temperatures were measured at the height of coral growth, usually about a foot from the bottom, at 30-foot intervals across the 450-foot width of the reef. The results are summarized in the chart, Figure 1 and presented in the same form as Mayer's cited above. On the basis of Mayer's results and theoretical considerations, the results obtained at Arno might have been predicted. The least range is found at the seaward edge, the greatest nearest shore, regardless of the state of the tide. Coral growth on the reef is closely correlated with this. It is richest at the reef margin where the temperatures are more constant, and weakest or absent near shore where temperature ranges are greatest. This correlation, of course, is not exclusively due to

temperature control. Agitation and water movements are greatest near the edge; salinity fluctuations due to heavy rainfall are greatest in the very shallow water near shore, among other controlling factors.

The fluctuation is diurnal. Early in the morning, before the sun shines on the reef flat, temperatures across the reef are nearly uniform, usually a degree less nearer shore than the normal 28 deg. C. at the reef margin, but within a few hours temperatures near shore, even at high tide, are much higher than at the margin.

Of particular interest are the two sets of serial temperatures graphically analyzed in Figure 16. These were run at 50-foot intervals along a line 1000 feet long and parallel to the reef edge and about 200 feet from shore, approximately on the boundary between the Acropora and Montipora zones. At the east end this line cuts across the transverse section line of serial temperatures shown in Figure 15. At high tide (10:30 a.m., 24 June) the water along this line was about 3-4 feet deep, and little variation in temperature was expected or found. With this depth of water the swells are little impeded and broken by the reef margin and no cause for fluctuation is developed. But at low tide (4:00 p.m., 23 June) great variation was found: from 28.2 to 30.9 deg. at more or less regular intervals along the tract. The highs were about 200 feet apart and alternated with the lows. These represent wedges of cooler water extending into the shoreward band of warmer water, or contrawise. The separation of these wedges is striking. At one spot a temperature difference of 1.5 deg. was found in a distance of only 25 feet.

The explanation of these wedges of warm and cool water at low tide is not hard to find. There is a close correlation between the wedges and the re-entrant channels in the reef margin. The cooler water wedges are opposite the re-entrants, the warmer wedges extend outward opposite the salients. At low tide the constant swells from the southeast, refracted around the easterly side of the atoll from the northeast, are slowed by the salients but move undiminished into the re-entrants. A wave of translation forms at the head of a re-entrant and is reinforced by refracted swells from the salient on either side. This drives a mass of cooler water onto the reef flat at each re-entrant. Rip currents moving outward onto the salients then shift the displaced warmer water toward the salients.

V. Appendix: List of Coral Genera Occurring at Arno

A. Scleractinia

Acanthastrea
Acrhelia
Acropora
Alveopora
Anacropora
Astreopora
Coscinaraea
Culicia
Cyphastrea
Echinopora
Favia
Favites
Fungia
Goniastrea
Goniopora
Halomitra
Herpolitha
Hydrophora
Leptastrea
Leptoseris
Leptoria
Lobophyllia
Merulina
Montipora
Mycedium
Pavona
" (Polyastra)
" (Pseudocolumnastraea)
Platygyra
Plesiastrea
Pocillopora
Porites
" (Synaraea)
Psammocora
" (Plesioseris)
" (Stephanaria)
Seriatopora
Stylocoeniella
Stylophora
Symphyllia
Ulophyllia

B. Alcyonaria

Heliopora
Tubipora

C. Hydrozoa

Distichopora
Millepora
Stylaster

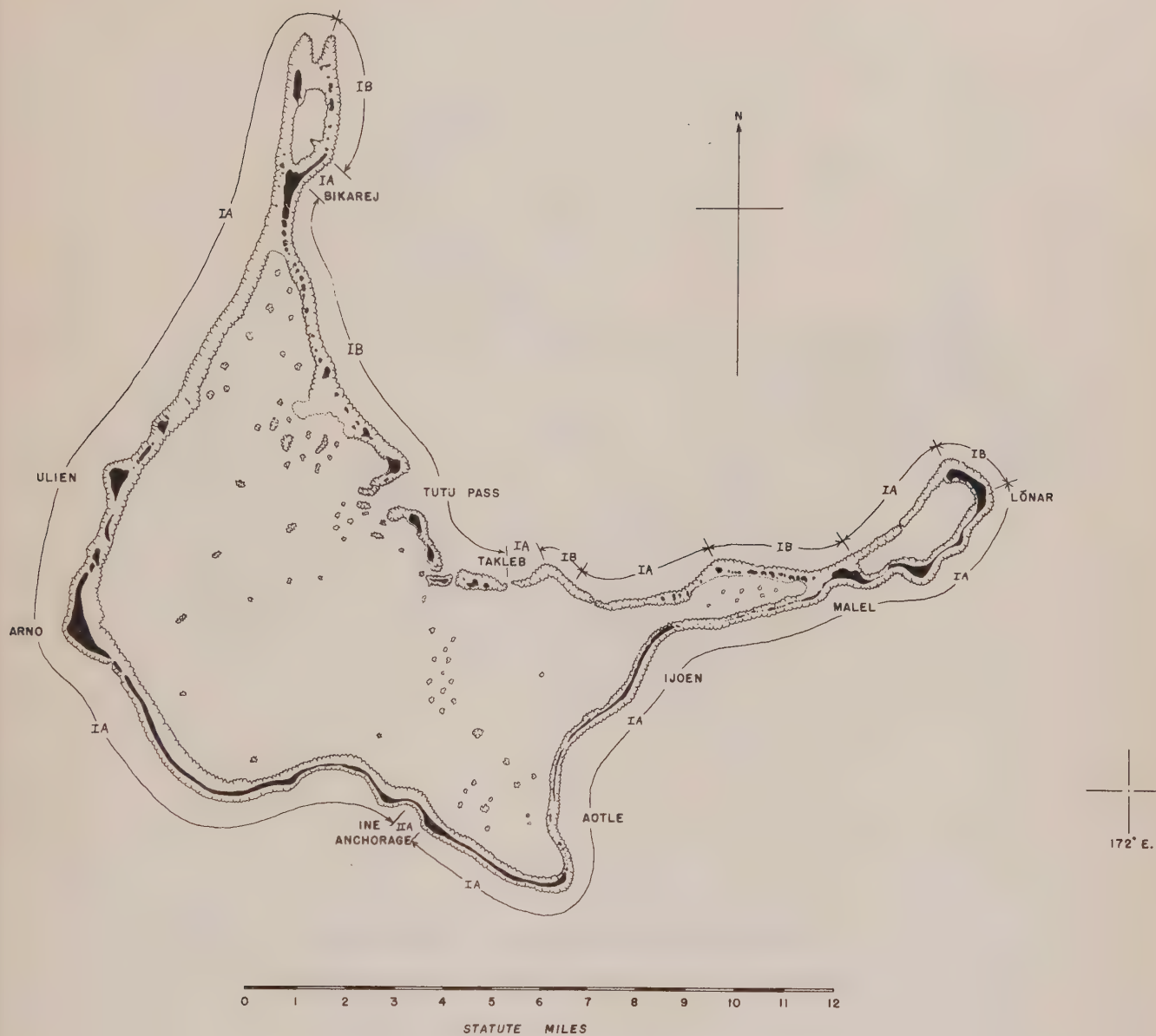


FIGURE 1. DISTRIBUTION OF REEF TYPES, ARNO.

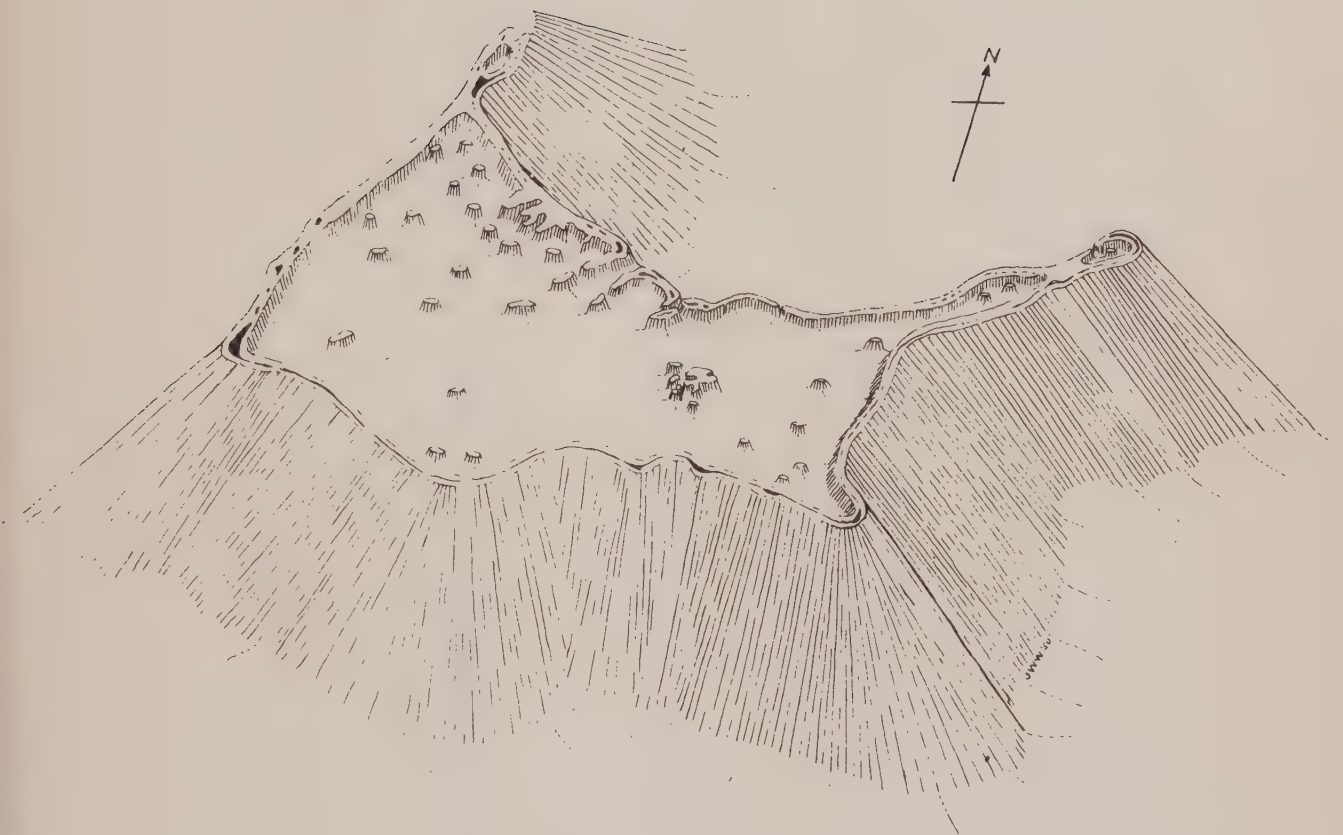


FIGURE 2. PHYSIOGRAPHIC DIAGRAM, ARNO ATOLL.

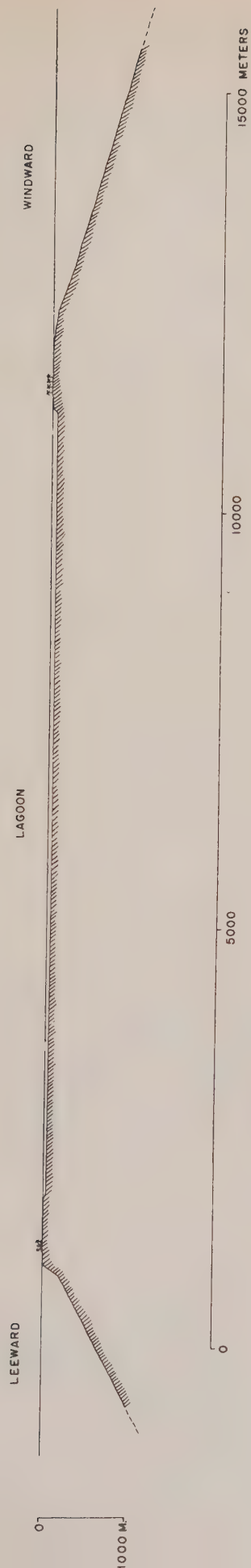


FIGURE 3. TRUE SCALE CROSS SECTION, ARNO ATOLL.

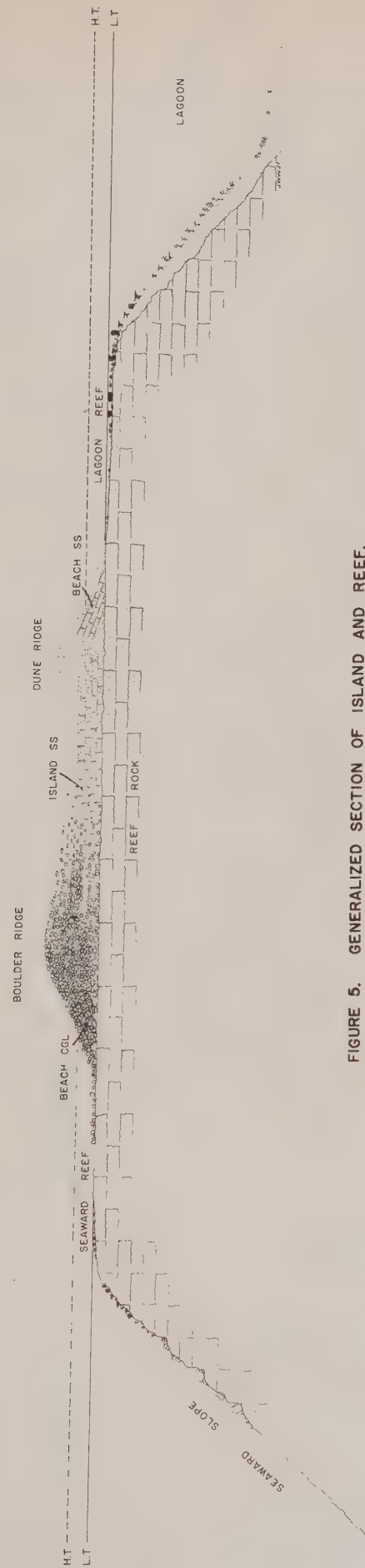


FIGURE 5. GENERALIZED SECTION OF ISLAND AND REEF.

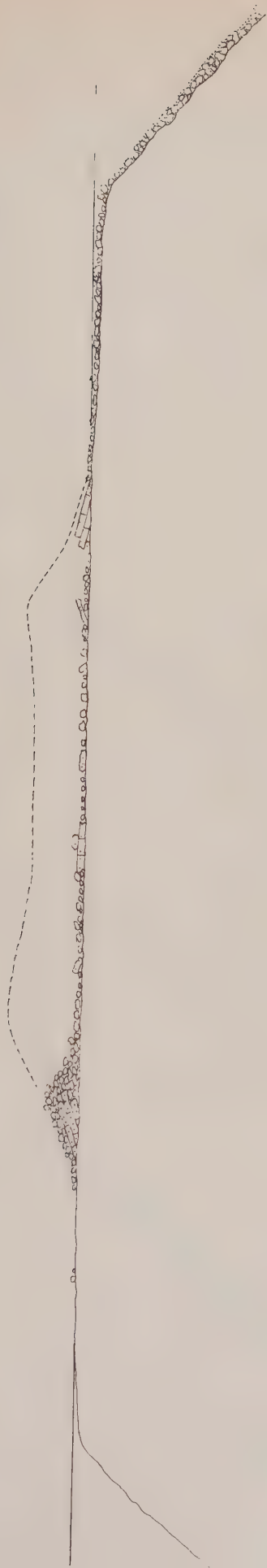


FIGURE 6. SECTION OF ISLAND SWEEP BY TYPHOON.

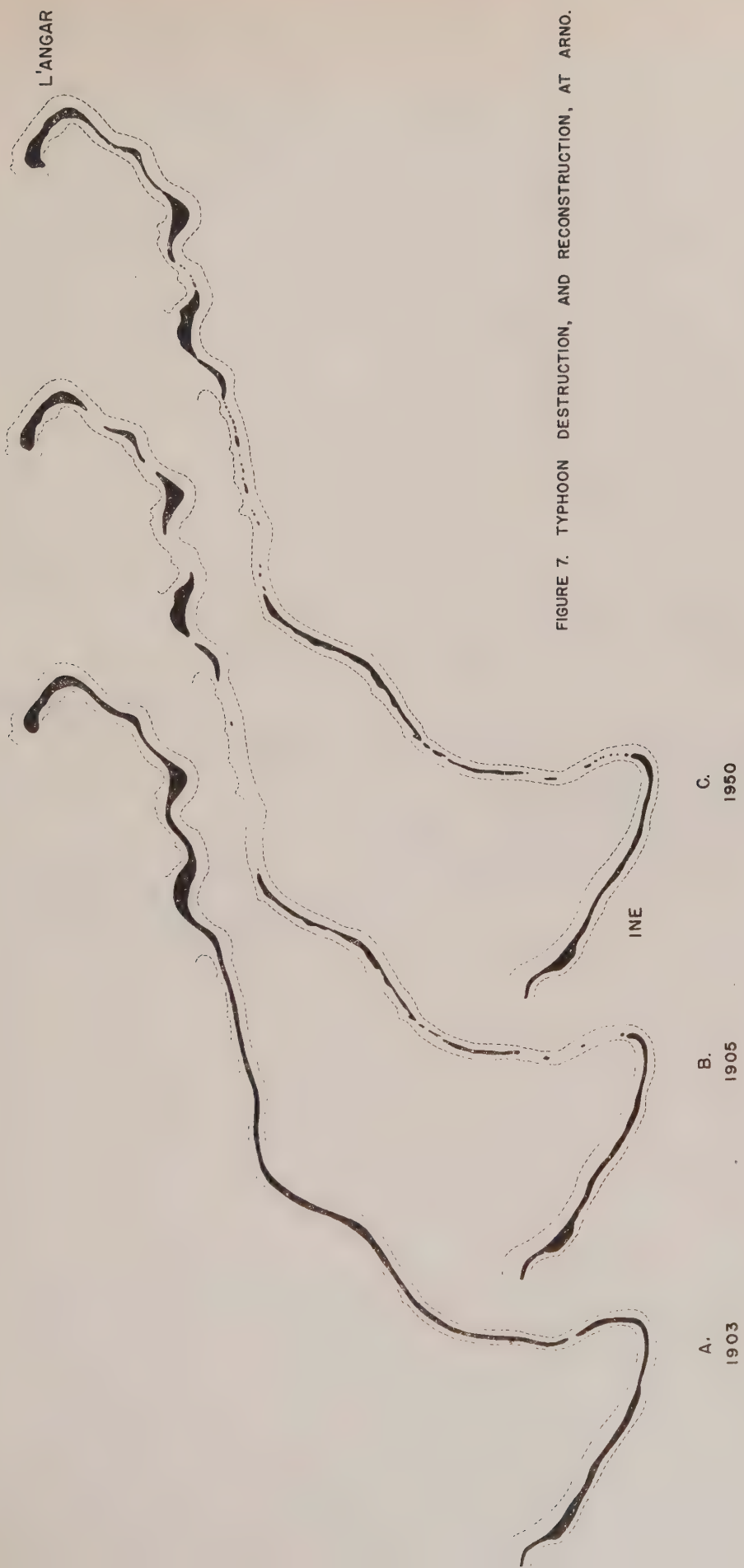
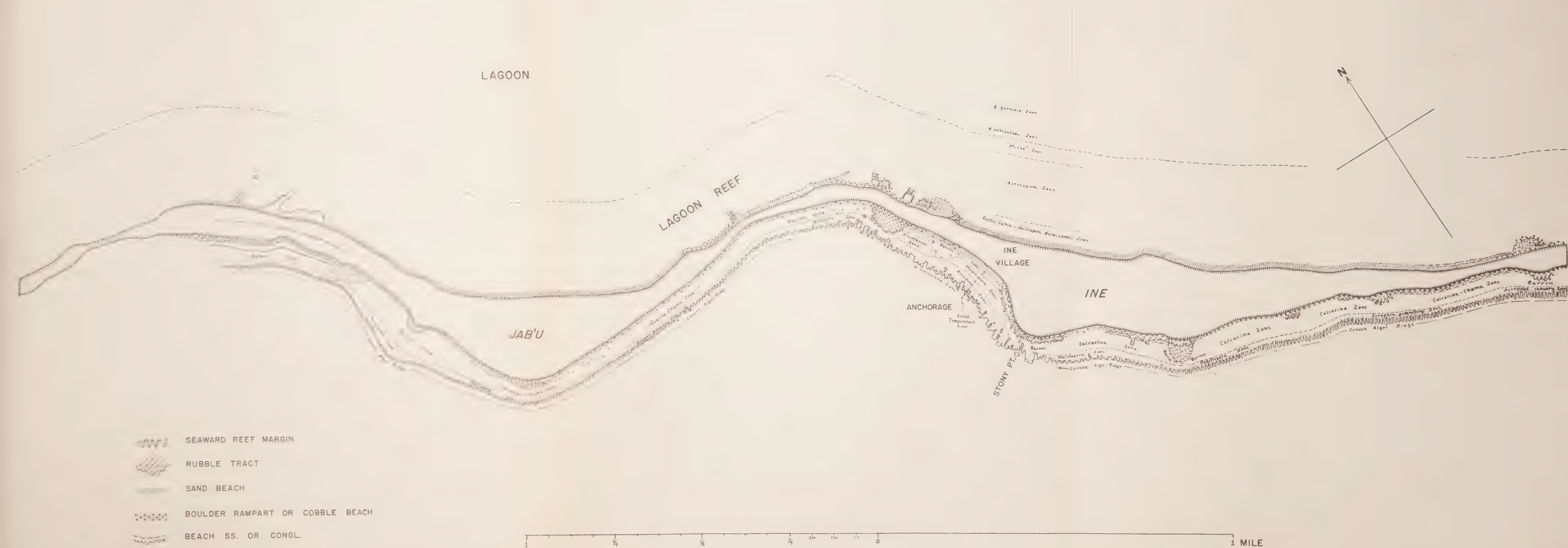


FIGURE 7. TYPHOON DESTRUCTION, AND RECONSTRUCTION, AT ARNO.



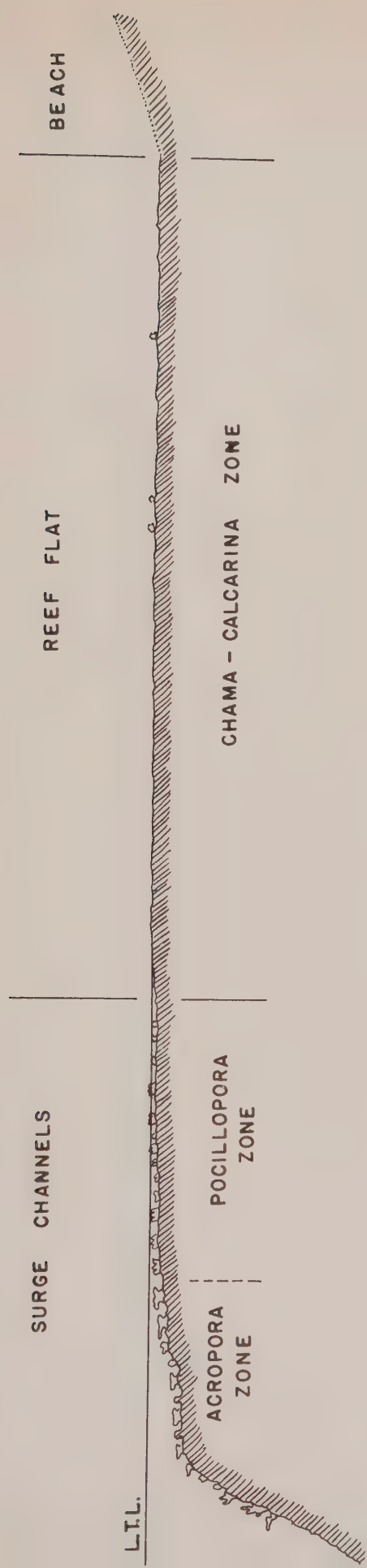


FIGURE 9. SEAWARD REEF, TYPE IA, INE I.

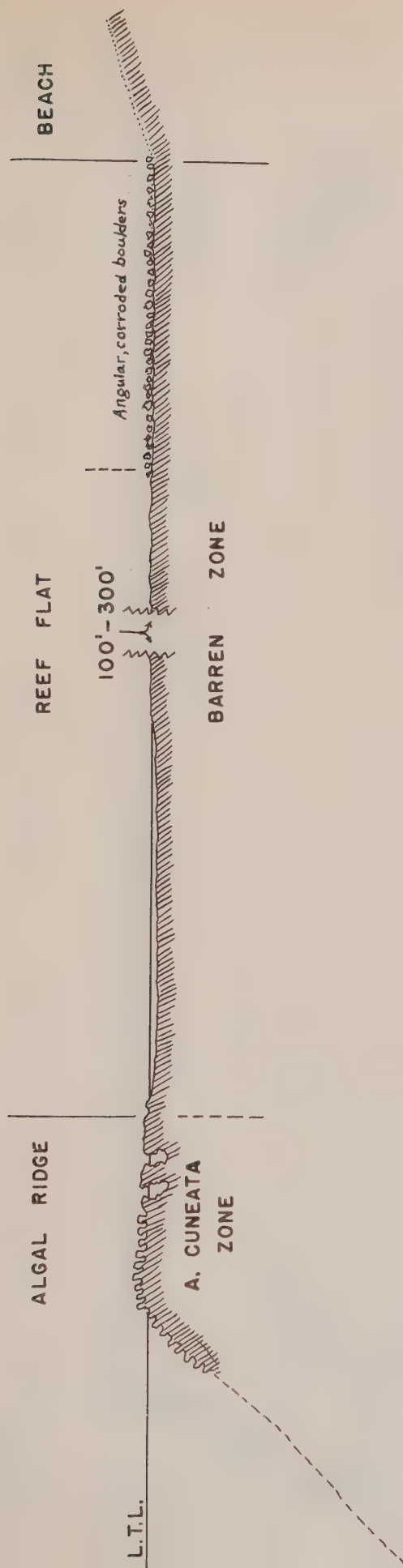


FIGURE 10. SEAWARD REEF, TYPE IB, TAKLEB I.

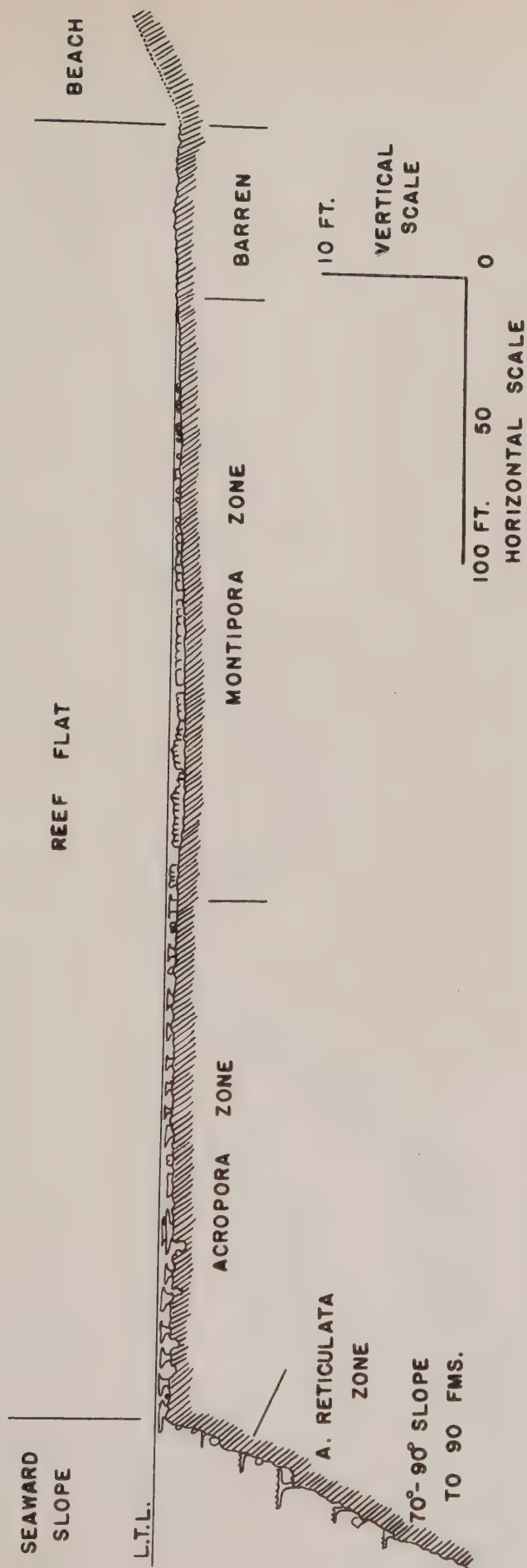


FIGURE 11. SEAWARD REEF, TYPE IIA, INE ANCHORAGE.

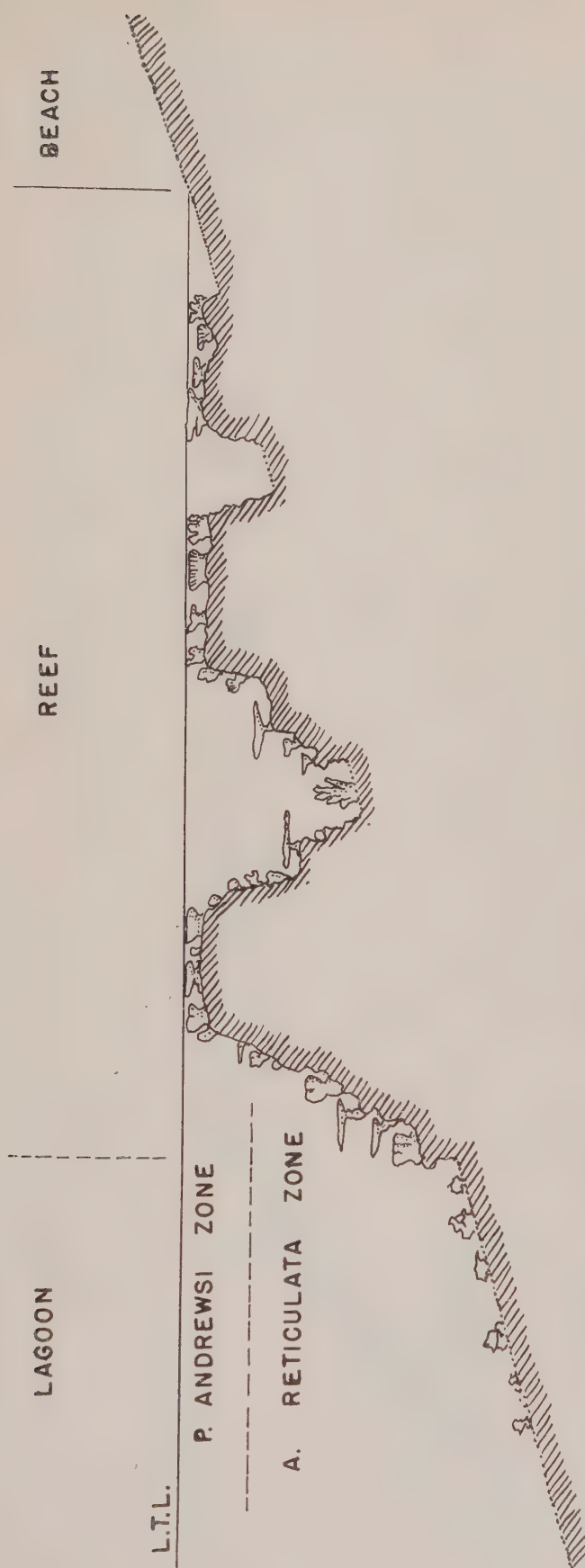


FIGURE 12. LAGOON REEF, LEEWARD TYPE, TAKLEB I.

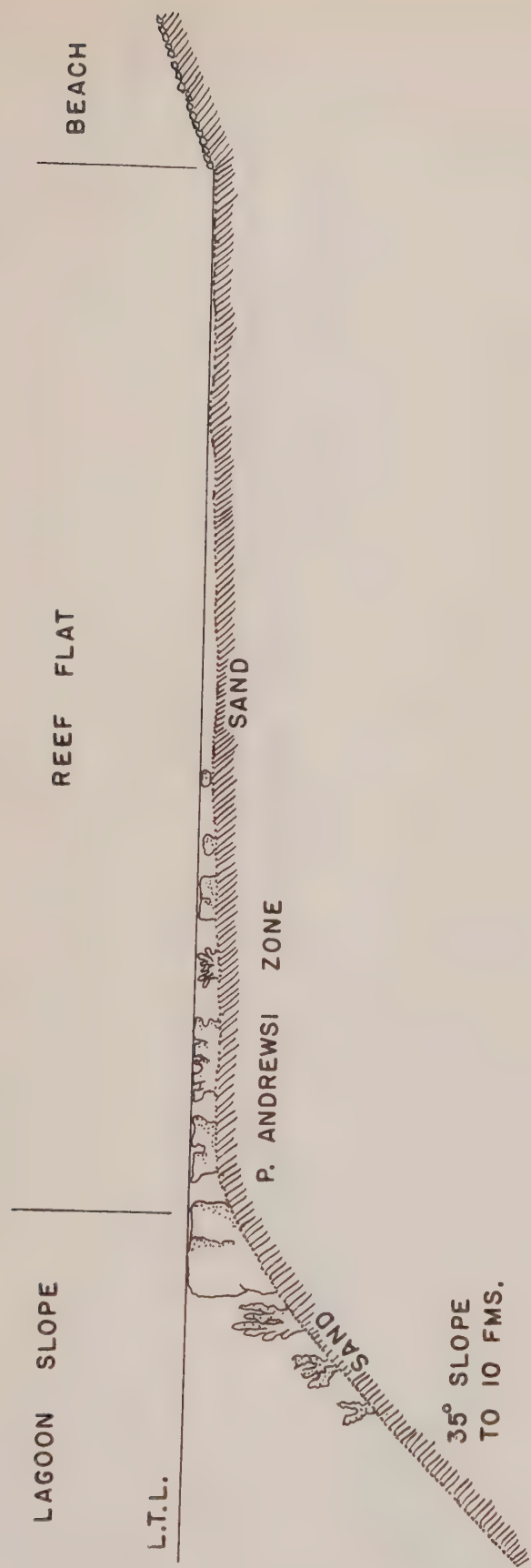


FIGURE 13. LAGOON REEF, ENCLOSED LAGOON, NORTH HORN.

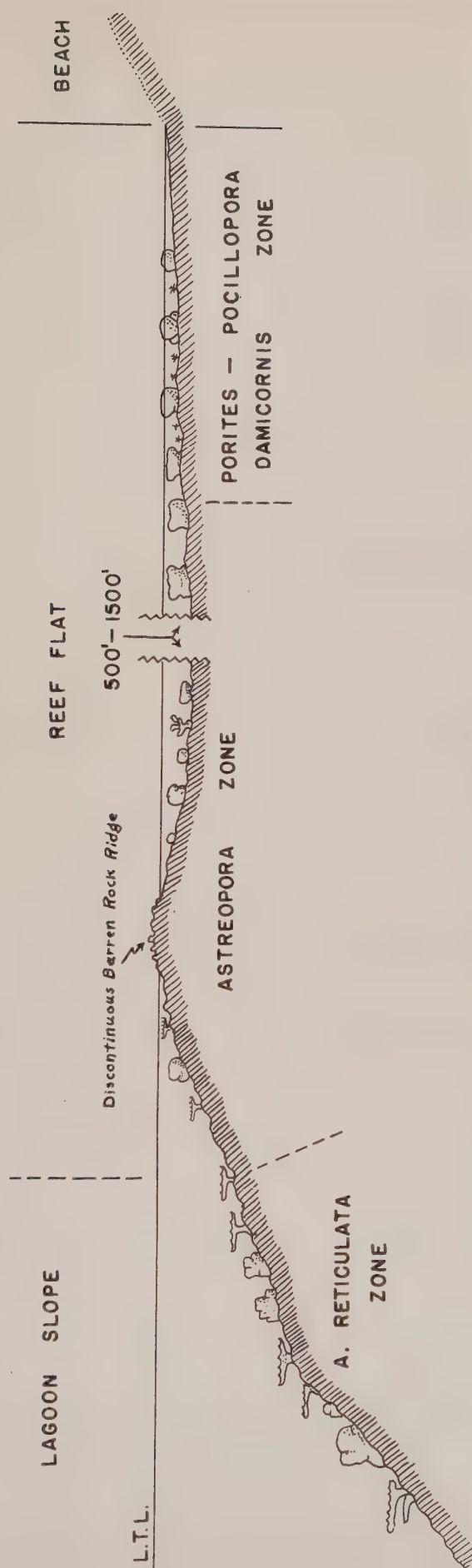


FIGURE 14. LAGOON REEF, WINDWARD TYPE, INE 1.

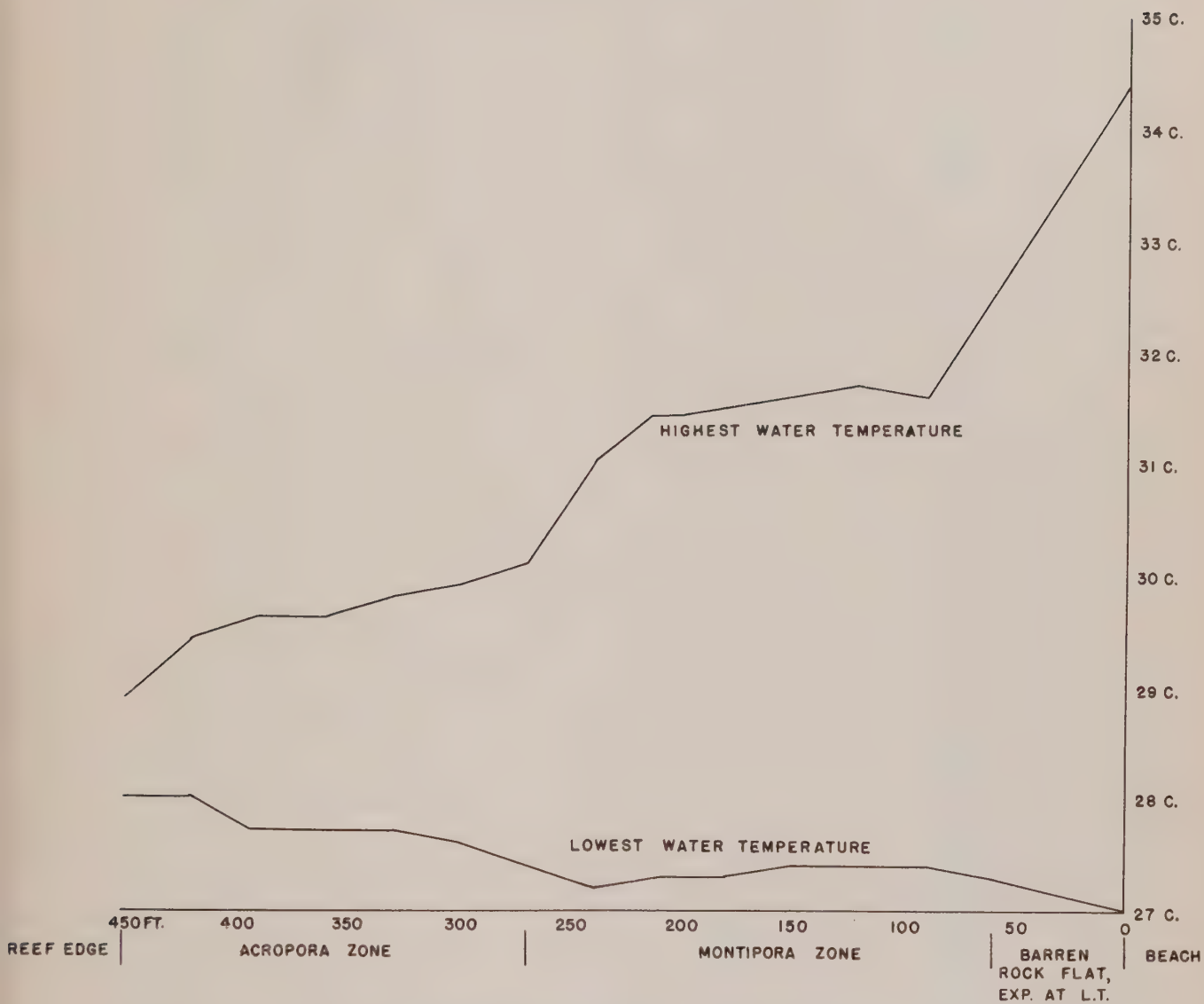


FIGURE 15. WATER TEMPERATURES ACROSS IINE ANCHORAGE REEF, JUNE, 1950.

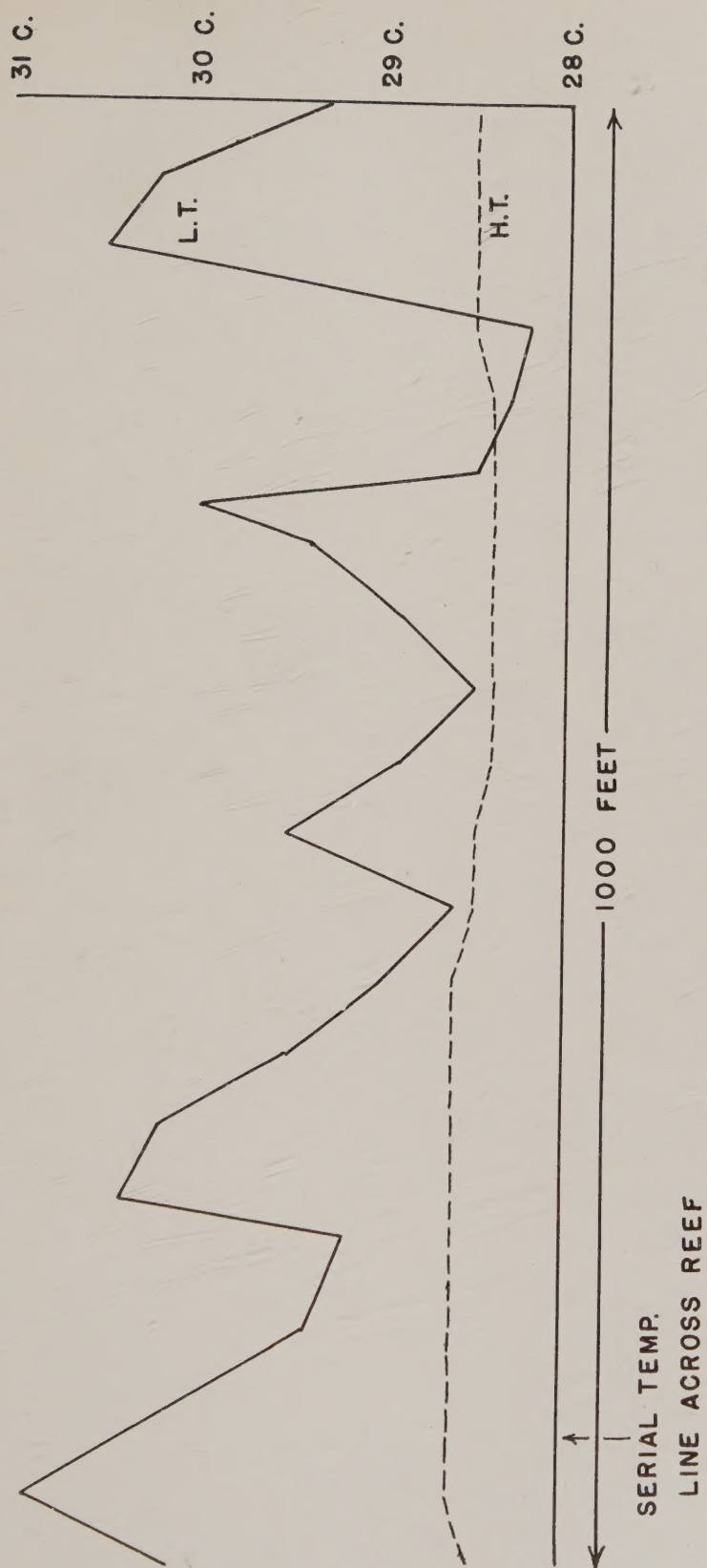


FIGURE 16. WATER TEMPERATURES ALONG INE ANCHORAGE REEF, INNER
EDGE OF ACROPORA ZONE.

